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ESTIMATES OF IONIZING RADIATION DOSES IN THE UNITED STATES 1960-2000

Alfred W. Klement, Jr., et al

Office of Radiation Programs
Rockville, Maryland

August 1972

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ESTIMATES OF IONIZING RADIATION DOSES IN THE UNITED STATES 1960-2000

DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE U.S.A.

ATOMIC ENERGY COMMISSION UNITED STATES OF AMERICA

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ESTIMATES OF IONIZING RADIATION DOSES IN THE UNITED STATES
1960-2000

Special Studies Group

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AUGUST 1972

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Radiation Programs
Division of Criteria and Standards
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PREFACE

The Federal Radiation Council* was established in 1959 to ". . . advise the President with respect to radiation matters, directly or indirectly affecting health, including guidance for all Federal agencies in the formulation of radiation standards and in the establishment and execution of programs of cooperation with States . . ." During that year a study was initiated to provide recommendations on radiation protection. As a result of these studies guidance was issued in 1960 and 1961.

In early 1970, the Federal Radiation Council recommended a review of the bases for and considerations of basic radiation guidance previously issued. The review was initiated in November 1970 by the appointment of temporary Council staff members by the participating agencies and contracting with the National Academy of Sciences and the National Council on Radiation Protection and Measurements for various parts of the review. Soon after, the Environmental Protection Agency was formed to which the Council's functions were transferred. The interagency review was continued under the auspices of this new agency in the Division of Criteria and Standards, Office of Radiation Programs, in which the Council temporary staff was assigned as the Special Studies Group.

This report is the first of several expected to result from the review of radiation guidance. It is an assessment of radiation doses in the United States from 1960 to 1970 and predictions to the year 2000. Its primary purpose is to provide other groups with some estimates of future doses to the United States population and major contributors to these doses that may assist in the formulation of general and specific radiation protection guidance.

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*Members of the Council were the Secretaries of Agriculture; Commerce; Defense; Health, Education, and Welfare; Interior; and Labor; and the Chairman of the Atomic Energy Commission. The Council's functions were transferred to the Environmental Protection Agency when the Agency was established in late 1970. (42 U.S.C. 2021(h).)

The report was made possible through the appointment of full-time staff and data furnished by the participating agencies. A number of other Federal and State agencies provided valuable information as well. A large number of persons in the participating and other agencies provided useful comments on the report as did a number of private organizations and individuals.

The participating agencies and their appointees were:

Department of Defense	Ramon P. Minx, LTC, MSC, USA
Department of Health, Education, and Welfare	Bernard Shleien, Pharm. D.
Atomic Energy Commission	Alfred W. Klement, Jr.
Office of Water Programs, Environmental Protection Agency	Carl R. Miller

A number of studies in progress or initiated during the review will provide additional information which will be valuable in assessing radiation doses in the future. More sophisticated methods are being developed and several sources are receiving more detailed study than they had prior to this review. In particular some sources are being studied which did not appear to contribute significantly to overall doses to the total United States population, but do contribute significantly to some individual doses. These and other studies of sources in this category would greatly assist in making more definitive dose estimates in future reviews of this nature.

In addition to the acknowledgements above, the authors gratefully acknowledge the assistance of Mr. Samuel Wieder, Editor, Radiological Health Data and Reports, for his editorial advice and assistance with the mechanics of preparation for publishing the report; Mrs. Yvonne Countee and Miss Barbara Stephens for assistance with early drafts of the report; and Mrs. Betty Cooke for preparation of the final typescript.

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I. INTRODUCTION

In June 1970, the Federal Radiation Council[1] initiated a review of the bases for and considerations of basic radiation exposure guidance issued in 1960 and 1961.[2,3] The study was continued by the Environmental Protection Agency following the transfer of the Council's functions to that agency.[4] This report contains the results of that part of the overall review concerned with estimates and predictions of radiation doses to United States populations - past, present, and future. Other parts of the review include a study of the scientific bases for estimating risk by a committee of the National Academy of Sciences, a review of models for estimating radiation doses by the National Council on Radiation Protection and Measurements, and a study of risk-benefit balancing. The overall study is scheduled to be completed by January 1973.

A. Purpose and Scope

The plan for study[5] listed as a component: "Collection and analysis of radiation exposure data relevant to the evaluation of risk and projections of major contributors anticipated in the future." To implement this provision of the plan the Special Studies Group (Temporary Staff) was directed to (1) collect, collate, and analyze information on radiation sources that contribute to radiation exposures of the general public and occupational exposures and (2) estimate the dose associated with each source or activity and total population dose.

The overall study was concerned with radiation guidance and the subject of other components of the study. The review reported here was made without regard to numerical values of current or possible future standards or regulations. Instead, practices believed prevalent during the periods under review were considered in order to provide an information base on which to evaluate current guidance.

Except for the obvious implication that radiation dose is related to effects, no expression or implication with regard to radiation effects is intended. This is a function of another component of the overall study.

Since estimation of radiation dose to human populations is the objective here, no discussion of the geographic distribution of radioactivity or radiation sources is included except where necessary to indicate procedures used for dose estimation. Such discussions are adequately included in other studies (e.g., Reference 6). Because the study is directed toward estimates and predictions of radiation doses to the population of the United States, emphasis is placed on the entire population averages. While special groups and unusual situations are considered and are included in the averages, no attempt is made to emphasize them. Although it was intended that only "major contributors anticipated in the future" be considered, some consideration was given to all sources to determine their degree of contribution. However, accidents and nuclear war were not considered. Obviously, some sources (including special cases mentioned above) were found to warrant only mention for completeness. It is recognized, however, that some of these pose serious problems in localized situations and are undergoing study by agencies responsible. Throughout this report the term "significant" is used in the sense that the estimates are or are not sufficient to be additive with regard to the accuracy of the estimates, considering the number of significant digits deemed appropriate. The term as used here is not related to radiation effects or risks.

The sources considered are categorized in sections as shown in the Table of Contents under the following topics: Environmental, Medical, Occupational, and Miscellaneous Radiation. Because of the nature of the various radiation sources and/or the nature of the available data, the sections differ in the manner of presentation.

B. General Procedures

For estimates of past doses from radiation the year 1960 was selected since Federal Radiation Council guidance was issued at about that time. For some categories other years were selected to provide a better overall view of the category. For the present, the year 1970 was selected, and for estimates of future doses, the years 1980, 1990, and 2000 were used.

Radiation doses are estimated* in most cases as annual doses. For long-lived radionuclides (e.g., ^{90}Sr and ^{239}Pu) 50-year internal doses are usually estimated; i.e., the dose accrued over 50 years from ingestion or inhalation of a nuclide during 1 year. Emphasis is placed on whole-body doses although organ doses are estimated when appropriate. Whole-body dose is defined as the average dose to the whole body. Use of the term somatic dose also refers to the average dose to the whole body, the magnitude of which, for purposes of this report, is assumed to be numerically equal to the average gonad dose. In all cases estimates are made of average doses to the population at risk (the population directly exposed by a radiation source) and to the entire United States population. This permits intercomparison of data from previous studies as well as from different radiation sources to both the population at risk and total populations. Doses are given in several ways suggested by some potential users of the information reported. The number of man-rem as used here is the product of an average dose and the population at risk associated with the average dose. The use of this unit is a convenient means of comparing doses from various sources, as well as averaging. All average annual doses are computed from the total man-rem divided by the total population for each population unit considered.

An attempt was made to make dose estimates as accurately as possible with the best data available. Estimates made by others were considered throughout the study. However, independent estimates were made during the study, although, as may be expected, many were in good agreement with estimates made by others. In a number of cases, no adequate similar projections were found. In nearly all cases, data available are only partially adequate for calculation of accurate doses since dose estimation in general is not the objective of data collection. In these cases, the assumptions made, the source of data, and the methods used are stated or referenced. In general, the nature of the data and the lack of good tests of the methods or models for dose estimation against measured doses are such that reasonably good estimates of the accuracy of the dose projections are impossible. The dose estimates for the past and present are believed to be correct well within a factor of two. Estimates for the future are probably correct within an order of magnitude. For some estimates, the number of digits shown is more than is warranted by the accuracy of the estimate. The purpose of this was to show trends which would not otherwise be seen, or to carry out additions to other values before rounding off.

---

*Reference 7 was used for basic concepts and data throughout.

C. Population Estimates

In this report, estimates of populations used for 1960 and 1970 are based on censuses[8,9] for those years. Estimates of future populations were based on the Bureau of the Census Fertility Assumption Series B.[10] For estimates of the size of populations at risk, generally those of others as referenced are used, but in some cases estimates were made during the study based on the 1960 census and extrapolated to the year 2000. Extrapolations are based on the same rate of increase as that for the entire United States or at the same rate as past years where data on populations at risk are available.

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II. ENVIRONMENTAL RADIATION

In this section, doses to the United States population resulting from all sources of environmental radiation are discussed. The sources include naturally occurring radionuclides and man-made environmental radioactive material resulting from nuclear explosives, the electrical power production process, and other governmental, industrial, medical, and research uses. For purposes of dose calculations, it is assumed that whole-body and gonadal doses are the same. Doses from worldwide ^{3}H and ^{85}Kr are discussed in Section D.

A. Natural Radiation

Man is exposed in varying degrees to sources of radiation found in nature depending on his activities and location. Cosmic radiation entering the earth's atmosphere and crust is one natural source of exposure. Nuclear interactions of cosmic rays with matter produce radiations and radionuclides to which man is exposed. Other sources of natural radiation affecting man are elements found in the earth's crust which are composed of one or more radioisotopes. These sources and estimates of their impact on United States populations are discussed below.

1. Cosmic Radiation

A number of reviews and data on cosmic radiation and cosmic radiation doses have been published.[1-7] The data from Reference 1 were used in the current estimates. Cosmic-ray dose rates vary with altitude and geomagnetic latitude up to about 50°. For example, whole-body dose rates at sea level from Alaska to Florida range from about 45 to 30 mrem/yr., and at 45° N. from sea level to 8,000 ft. altitude, the range is about 40 to 200 mrem/yr. Based on such relationships, estimates of doses were made for each county or similar political unit in the United States. Averages for each major political unit of the United

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States, calculated from the man-rem totals of the smaller political units, are shown in Table II-1. These are similar to estimates made by others using similar methods[8]. (Revisions of Reference 7 in preparation at the time this report was being finalized indicate that the estimates at the highest altitudes may be somewhat too high[9]. However, the overall average would not be significantly different.)

Table II-1

Estimated Annual Cosmic-ray Whole-body Doses
(mrem/person)

Political Unit	Average Annual Dose
Alabama	40
Alaska	45
Arizona	60
Arkansas	40
California	40
Colorado	120
Connecticut	40
Delaware	40
Florida	35
Georgia	40
Hawaii	30
Idaho	85
Illinois	45
Indiana	45
Iowa	50
Kansas	50
Kentucky	45
Louisiana	35
Maine	50
Maryland	40
Massachusetts	40
Michigan	50
Minnesota	55
Mississippi	40
Missouri	45
Montana	90
Nebraska	75
Nevada	85
New Hampshire	45
New Jersey	40
New Mexico	105
New York	45
North Carolina	45
North Dakota	60
Ohio	50
Oklahoma	50
Oregon	50
Pennsylvania	45
Rhode Island	40
South Carolina	40
South Dakota	70
Tennessee	45
Texas	45
Utah	115
Vermont	50
Virginia	45
Washington	50
West Virginia	50
Wisconsin	50
Wyoming	130
Canal Zone	30
Guam	35
Puerto Rico	30
Samoa	30
Virgin Islands	30
District of Columbia	40
Total United States	45

2. Terrestrial Radioactivity

Terrestrial radioactive material is present in the environment because naturally radioactive isotopes are constituents of a number of elements in the earth's crust. The nuclear interaction of cosmic rays with nuclei in the atmosphere, soil, and water also produce several radionuclides. The naturally occurring radionuclides give rise to both external and internal irradiation of man. Reviews and listings of literature on environmental levels of these nuclides are available[10-12].

a. External Gamma Radiation

The significant external gamma exposures are produced by ^{40}K and th decay products of the uranium and thorium series. Exposures from radon and radon daughters vary significantly with atmospheric conditions which affect radon concentrations at ground level as discussed below. Also, the condition of the surface (soil moisture, porosity, cultivation, pavement, etc.) affects exposure rates. Therefore, in addition to variation with geological and geographical factors, exposure rates vary in time and specific location.

Based on several hundred reported measurements[13-16] with scintillation spectrometers, estimates have been made[16,17] of the range and mean of whole-body doses by population and by areas for the United States. Ninety percent of all areas fall in the range of 15 to 130 mrem/yr., while 90% of the population falls in the range of 30 to 95 mrem/yr. The estimated mean was given as 55 mrem/yr.

In the present study, the above referenced data were used to estimate average dose rates for counties where measurements were made. From these county measurements, an average was calculated for each State. These were then used to estimate the average for the United States population. For these estimates it is assumed that the variability within and among the various political units is the same as that of the reported measurements. Where measurements were made at different times in the same locations, the average was used to account for variations in time so far as the data permitted. Based on these assumptions and procedures, the overall United States average dose was estimated to be 60 mrem/yr., which is near that estimated by other procedures mentioned above. The averages for each State are shown in Table II-2. Populations of political units shown by asterisks were assumed to have the same doses as the United States average as reasonabl estimates. A factor of unity was used in these estimates for conversion of open-field air-dose measurements to whole-body doses.

Table II-2

Estimated Annual External Gamma Whole-body Doses from Natural Terrestrial Radioactivity
(mrem/person)

Political Unit	Average Annual Dose
Alabama	70
Alaska	60*
Arizona	60*
Arkansas	75
California	50
Colorado	105
Connecticut	60
Delaware	60*
Florida	60*
Georgia	60*
Hawaii	60*
Idaho	60*
Illinois	65
Indiana	55
Iowa	60
Kansas	60*
Kentucky	60*
Louisiana	40
Maine	75
Maryland	55
Massachusetts	75
Michigan	60*
Minnesota	70
Mississippi	65
Missouri	60*
Montana	60*
Nebraska	55
Nevada	40
New Hampshire	65
New Jersey	60
New Mexico	70
New York	65
North Carolina	75
North Dakota	60*
Ohio	65
Oklahoma	60
Oregon	60*
Pennsylvania	55
Rhode Island	65
South Carolina	70
South Dakota	115
Tennessee	70
Texas	30
Utah	40
Vermont	45
Virginia	55
Washington	60*
West Virginia	60*
Wisconsin	55
Wyoming	90
Canal Zone	60*
Guam	60*
Puerto Rico	60*
Samoa	60*
Virgin Islands	60*
District of Columbia	55
Others	60*
Total United States	60

*Assumed to be equal to the United States average.

There have been unpublished reports of residences built on tailings piles at some abandoned uranium mills, as well as various uses of tailings, such as in construction materials. Based on the little information available, doses from these sources received by relatively small populations are estimated to be insignificant in terms of overall averages or total man-rem. For example, measurements have been made[18] at Grand Junction, Colorado, from which dose estimates can be made. These measurements showed an average of 107 mrem/yr. in living areas of residences (above outdoor doses) to a population of about 1,800, or about 200 man-rem/yr. A very gross estimate for all such situations may be 10 to 20 times this value. This could increase the average dose for the population of Colorado by less than 0.1 mrem/yr. Since remedial measures are being taken to prevent similar situations in the future and to reduce these doses, future doses are expected to be less than current ones.

b. Internal Radiation

While all of the natural radionuclides contribute to internal radiation doses, only a few are found to be significant. These include ^{3}H, ^{14}C, ^{40}K, and ^{226}Ra and ^{228}Ra and their decay products. Within the United States ^{3}H and ^{14}C are relatively uniformly distributed so that their levels in foods and water do not vary appreciably with geographical location. This is largely true for ^{40}K because of agricultural practice[10] (fertilizing, cultivation methods, etc.). Radium and ^{210}Po are similarly affected to some extent. These facts and the practice in the United States of widespread manufacturing and transportation of foods and people have an "averaging" effect on radionuclide contents of diets throughout all geographical areas. For example, the concentrations of ^{226}Ra in dietary samples vary as much or more at individual locations than overall location averages differ from an average for the United States.[10,17,19] Because of this, it appears reasonable to assess internal radiation doses from dietary sources in the United States as a whole rather than attempt an assessment by geographical or political unit.

Radon is the only significant natural radionuclide leading to widespread exposure through inhalation. It is released from soil, rock, and building materials and contained in natural gas and other fossil fuels. Radon concentrations vary considerably with atmospheric and soil conditions as mentioned above. Continuous monitoring records show that in many locations over extended periods of time air concentrations vary both diurnally and seasonally.[20,21] Rainstorm and wind effects are also seen.[21] Further variations in concentrations would be expected with regard to radon resulting from burning of natural gas and other fossil fuels. Radon in natural gas would increase ambient concentrations in dwellings, as well as the general environment, depending on type of construction and ventilation of dwellings and perhaps some other factors.[22] While some studies are in progress in this regard, insufficient data are available at this time to provide a basis for a reasonable estimate of the natural gas contribution to population doses. Other fossil fuels would contribute additional radon to the general environment, and would be included in outdoor measurements. The estimated whole-body dose from dissolved radon in the body is 3 mrem/yr.[1] Estimates for lung doses from inhaled radon have ranged from about 100 to 900 mrem/yr.[1]

The estimated average internal dose rates to the population of the United States are summarized in Table II-3. These estimates are quite similar to those reported by others.[2,9,17]

Table II-3

Estimated Average Annual Internal Radiation Doses from Natural Radioactivity in the United States

	Annual Doses (mrem/person)		
Radionuclide*	Whole-body	Endosteal Cells (Bone)	Bone Marrow
^{3}H	0.004	0.004	0.004
^{14}C	1.0	1.6	1.6
^{40}K	17	8	15
^{87}Rb	0.6	0.4	0.6
^{210}Po	3.0	21	3.0
^{222}Rn	3.0	3.0	3.0
^{226}Ra	-	6.1	0.3
^{228}Ra	-	7	0.3
TOTAL	25	47	24

*Other natural radionuclides would contribute to doses but such a small fraction that they would not affect the totals within the accuracy of these estimates. As an example, doses from ^{3}H are shown here.

3. Summary

The overall estimates of doses from natural radiation are summarized in Tables II-4 and II-5.

Table II-4

Estimated Total Annual Average Whole-body Doses from Natural Radiation in the United States (mrem/person)

Source	Annual Doses
Cosmic rays	45
Terrestrial radiation	
External	60
Internal	25
TOTAL	130

Table II-5

Estimated Total Annual Whole-body Man-rem from Natural Radiation in the United States

Year	Population (millions)	Annual Man-rem (millions)
1960	183	23.8
1970	205	26.6
1980	237	30.8
1990	277	36.0
2000	321	41.7

B. Global Fallout from Nuclear Tests

Fallout from nuclear weapons tests is another source of environmental radioactive material. Large-scale, high-yield atmospheric test series in the past (e.g., United States and Soviet tests, 1961 to 1962) introduced radioactive material into the stratosphere which was later deposited worldwide. The last such test series was conducted in 1962. A portion of the small amount of material remaining in the stratosphere continues to be deposited annually. During the past several years, a few atmospheric tests by the French and Chinese have been conducted which have been sufficient to maintain a relatively constant annual fallout deposition.[23] Past and current tests have also injected material into the troposphere which is deposited relatively quickly within a few degrees of the latitude of the tests. (Local fallout from Nevada Test Site tests is discussed in II. E; and worldwide ^{3}H and ^{85}Kr doses are discussed in II. D.)

Both current fallout and that deposited from past tests contribute to internal and external population doses. For this study, it was assumed that the rate and type of testing from 1965 to 1970 will continue through 2000. Estimates were made for 1963, 1965, 1969, and subsequent decades to 2000. In 1963 the highest fallout deposition occurred. The year 1969 was chosen as an example of the current situation.

1. External Gamma Radiation

The accumulation of ^{137}Cs deposited from past nuclear tests is the major source of long-lived external gamma radiation from fallout. A number of short-lived radionuclides contribute significantly to doses within a few years of their production. Estimates of external gamma doses from fallout in the New York City area have been made which were verified by measurements.[24,25,26] Those values are the basis for the 1963 estimates in this study and an extension was used to estimate doses from short-lived nuclides in other years. Estimates of doses from ^{137}Cs for 1965 and 1969 were based on ^{90}Sr deposition data for New York City.[23] Two population areas were used for this purpose -- "wet" and "dry" areas.[27,28] The average annual deposition of ^{90}Sr in "wet" areas is estimated to be 0.74 times that for New York City.[23,28] Based on measurements in 1963, deposition in "dry" areas was estimated to be 55% of that in "wet" areas (or 41% of that for New York City). The population in "dry" areas was calculated to be 15% of the United States population.

It is assumed that ^{137}Cs deposition is 1.6 times[29] that of ^{90}Sr, and that the factor[25] for conversion of ^{137}Cs deposition values to open-field exposure rate is 1.7×10^{-3} (μR/hr.)/(mCi/mi.^{2}). Exposure rates (μR/hr.) are then converted to air dose rates (μrad/hr.). A shielding factor[30] of 0.4 due to buildings and other structures and a screening factor[31] of 0.8 caused by body shielding were assumed for conversion of open-field air doses to whole-body doses.

Similarly, average dose estimates were made for short-lived radionuclides based on the study mentioned above.[24] There was no significant contribution from these nuclides in 1969.

The calculated total annual average external gamma radiation doses to the United States population for 1963, 1965, and 1969 were 5.9, 1.8, and 0.9 mrem/person, respectively. Annual doses from 1970 to 2000 are estimated to be about the same as those for 1969.

2. Internal Radiation

Whole-body and individual organ doses have been estimated for inhalation and ingestion of fallout radionuclides.

a. Inhalation

Radionuclide air concentration data[32,33] were used to determine doses to the lungs, bone, respiratory lymph nodes, and whole body due to inhalation. The average air concentration from the United States data was applied to the country as a whole. Dose values for individual radionuclides were obtained by comparison with recommended maximum air concentrations[34] or by using values of dose to be received by the individual per unit of activity inhaled.[35,36] The results are given in Table II-6.

Most doses are received within 1 year after exposure. However, the doses from ^{90}Sr and plutonium will be received over the 50 years following inhalation because of their long physical and biological half-lives. The fraction of the respiratory lymph node dose from plutonium delivered by a certain time after a 1-year exposure can be estimated from Figure II-1. No attempt has been made to determine the total accumulated dose from the inhalation of plutonium since air concentration data are not available for many years during the fallout period. The accumulation of ^{90}Sr doses is discussed further in the next section.

b. Ingestion

Doses due to ingestion of ^{89}Sr, ^{90}Sr, ^{131}I, and ^{137}Cs have been estimated using diet radionuclide concentration data from 12 cities.[37,38] (Tritium is discussed in section D.3) Strontium-89 and ^{131}I doses are assumed to result entirely from a milk intake of 1.2 liters/day. (The slightly higher-than-average milk intake will account for doses from other food sources.) The United States was divided into 12 regions with

Table II-6

Estimated per Capita Organ Doses from Inhalation of Radioactive Fallout

(mrem accrued/yr.)

Nuclide	Lung Dose[a]			Bone Dose[a]			Whole-body Dose		
	1963	1965	1969	1963	1965	1969	1963	1965	1969
^{54}Mn[c]	0.96	0.16	—[b]	—	—	—	0.01	—	—
^{55}Fe[c]	0.02	0.01	—	—	—	—	—	—	—
^{89}Sr[c]	0.60	0.01	—	0.08	—	—	0.03	—	—
^{90}Sr[c,d]	0.43	0.09	0.01	0.28[f]	0.06	0.01	0.40[f]	0.09	0.01
^{95}Zr[c]	1.9	0.02	0.05	0.62	—	0.02	0.16	—	—
^{109}Cd[c]	—	0.01	—	—	—	—	—	—	—
^{137}Cs[c]	0.23	0.06	0.01	0.03	—	—	0.02	—	—
^{144}Ce[c]	8.2	0.38	0.31	10.6	0.49	0.40	0.55	0.02	0.02
^{238}Pu[d]	0.35[g]	0.06	0.08	0.14[f]	0.03	0.03	0.01[f]	—	—
^{239}Pu[e]	4.5[g]	0.78	0.16	1.9[f]	0.35	0.07	0.19[f]	0.04	0.01
TOTALS	17.0	1.6	0.6	14.0	0.9	0.5	1.4	0.2	0.04

Nuclide	Respiratory Lymph Node Dose[a]		
	1963	1965	1969
^{238}Pu[d]	79[f]	14	19
^{239}Pu[e]	1,000[f]	175	36
TOTALS	1,080	190	55

[a] Does not include whole-body dose.

[b] Dose <0.01 mrem/yr.

[c] From comparison with recommended MPC_a limits.[34]

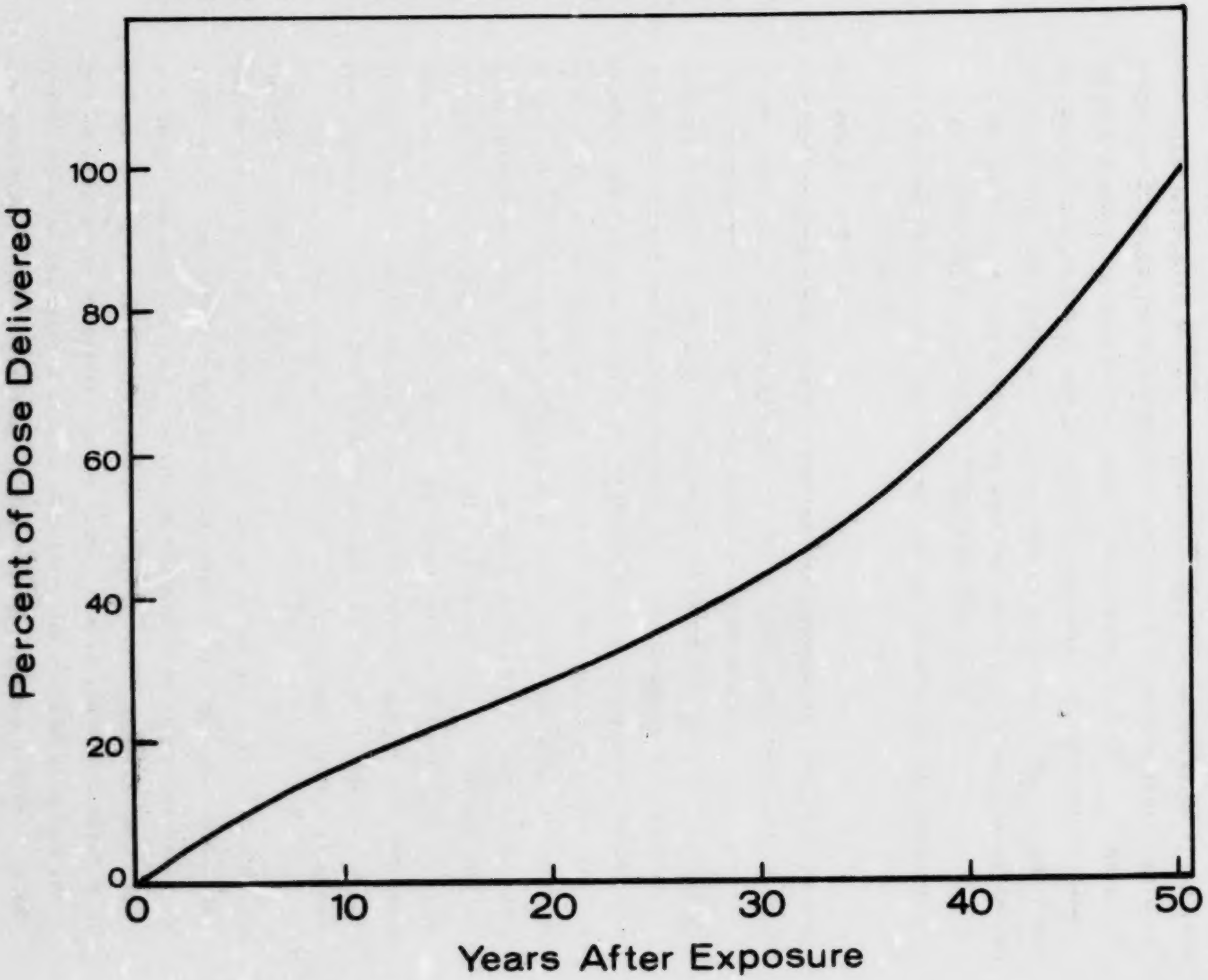
[d] From dose values in Reference 35.

[e] From dose values in Reference 36.

[f] 50-year dose for a 1-year intake (see text);
25% ^{90}Sr dose given in 1st 5 years,
9% Pu dose given in 1st 5 years.

[g] 50-year dose for a 1-year intake (see text);
40% given in 1st year.

Figure II-1. Respiratory Lymph Node Dose from a One-Time Exposure to Plutonium (Percent Delivered vs. Years After Exposure; Adapted from Reference 36).



one designated city considered representative of each region. Using values of dose per unit activity ingested,[35] an average dose for the United States was obtained. Doses from ^{14}C were estimated using a percent of ^{14}C above natural levels in the body of 30% for 1963, 70% for 1965, and 60% for 1969[39] with the natural dose levels as given in Table II-3. The results are given in Table II-7. All the doses are delivered in 1 year except the ^{90}Sr doses which are delivered over the 50 years following ingestion.

Because of the long delivery time of ^{90}Sr doses, Figure II-2 has been prepared so that the accumulated dose to a cohort population of a certain age in any given year can be determined. The method and values used in constructing this figure are presented in Appendix II-A. The shapes of the curves are affected by the amount of ^{90}Sr intake and its long-term retention in bone. The average accumulated dose to an individual in the cohort population can be read from the chart by using the year in which the given age is attained and the graph for that age. For example, in 1970 the average 20-year-old person would have accumulated a bone dose of about 260 mrem from ^{90}Sr. Repeating this at 10-year intervals gives the average individual accumulated dose as a function of age. Figure II-3 shows this for several cohort populations. These values represent a United States average and any one individual's actual dose may vary by more than a factor of two because of variation in fallout and in diet.

3. Summary

The aggregate doses (except for ^{3}H) are summarized in Table II-8.

C. Peaceful Applications of Nuclear Explosives

A number of possible uses of nuclear explosives have been suggested for industrial applications. These include excavation, gas stimulation, recovery of oil from oil shale, mineral recovery, underground storage, waste and water management, and use of geothermal energy.[40-42] Experimental programs in these areas have progressed to some extent. This is especially true with regard to excavation and gas stimulation which lack relatively little additional experimentation for complete development of capabilities and proven economic advantage. However, development has not

Table II-7

Estimated Dose from Ingestion of Radioactive Fallout
(mrem accrued/yr./person)*

	^{14}C		^{137}Cs	^{89}Sr	^{90}Sr		^{131}I
Year	Whole-body	Bone	Whole-body	Bone	Whole-body	Bone	Thyroid
1963	0.3	0.5	4.3	1.3	7.3	73	25
1965	0.7	1.1	2.3	0.2	7.2	72	4
1969	0.6	1.0	0.4	0.2	3.2	32	3
1980	0.6	1.0	0.4	0.2	3.2	32	3
1990	0.6	1.0	0.4	0.2	3.2	32	3
2000	0.6	1.0	0.4	0.2	3.2	32	3

*The $^{90}_{34}$Sr doses are delivered over 50 years. The whole-body dose = 0.1 times the dose to bone. Yearly ^{90}Sr whole-body dose rates estimated from Figure II-3 for the years considered are:

1963 = 0.9 mrem/yr.
1965 = 1.9 mrem/yr.
1969 = 2.1 mrem/yr.
1980 = 2.5 mrem/yr.
1990 = 2.7 mrem/yr.
2000 = 3.0 mrem/yr.

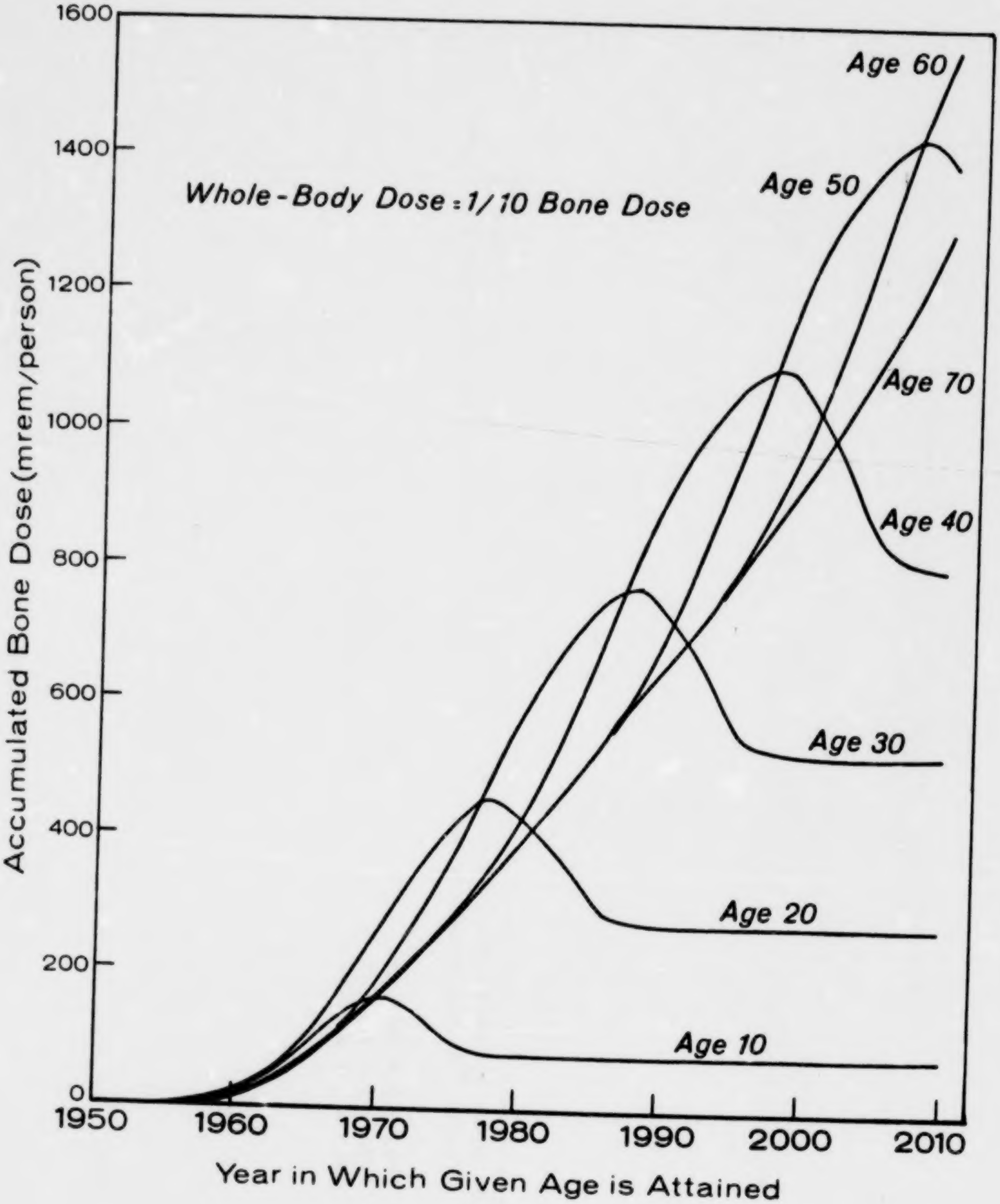


Figure II-2. Accumulated Bone Dose from ^{90}Sr for Various Ages (U.S. Average).

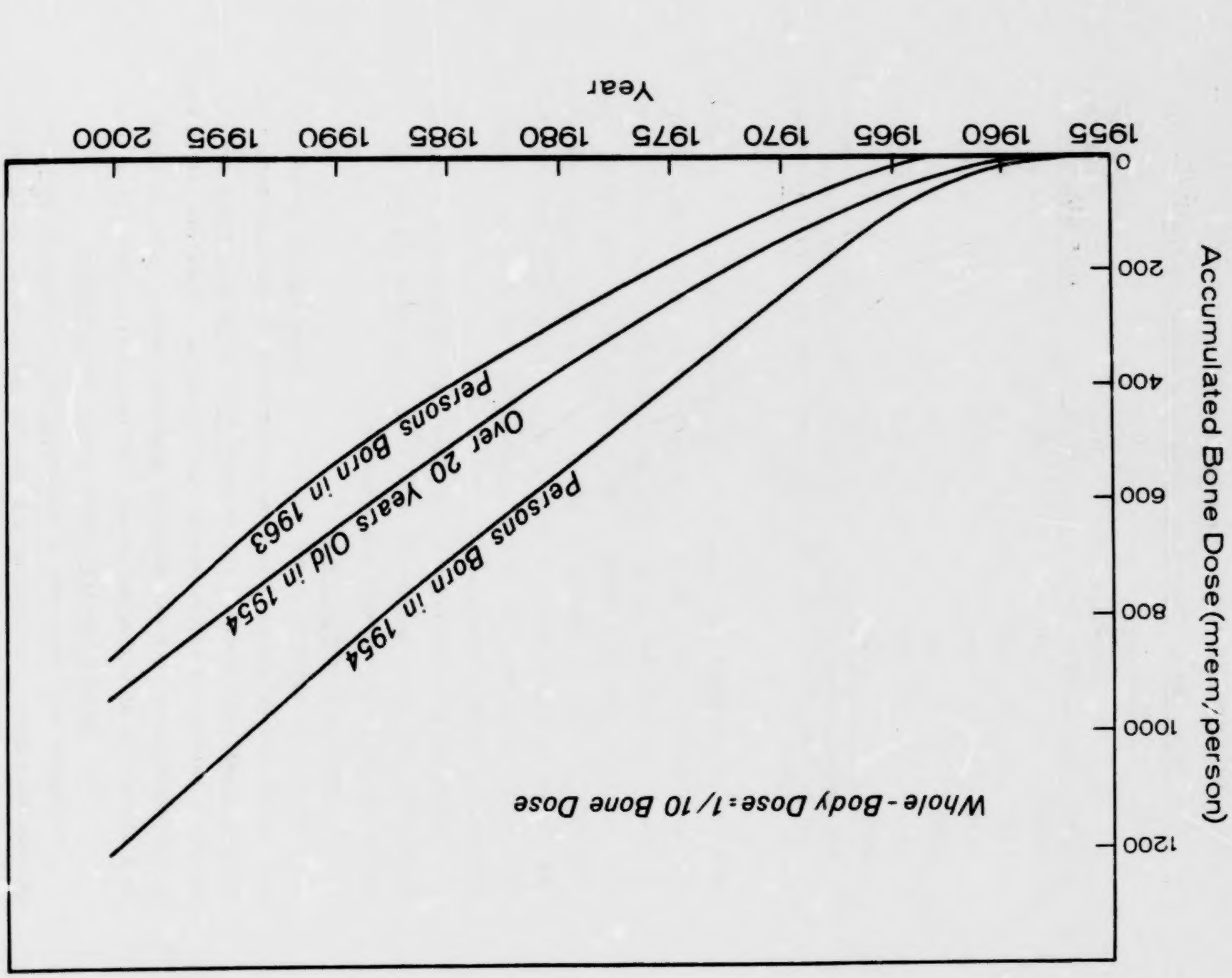


Figure II-3. Accumulated ^{90}Sr Bone Dose by Several Cohort Populations (U.S. Average).

Table II-8

Total Annual Whole-body Doses from Global Fallout*

Year	U.S. Population (millions)	Per Capita Dose (mrem)	Man-rem for U.S. Population (millions)
1963	190	13	2.4
1965	194	6.9	1.3
1969	204	4.0	0.82
1980	237	4.4	1.1
1990	277	4.6	1.3
2000	321	4.9	1.6

*Internal whole-body dose rate values for ^{90}Sr are taken from the footnote of Table II-7. Tritium is excluded here and is considered in II.D.3.

advanced to the stage where reasonably accurate estimates of the radiological impact of future usage can be made. Also, in general, applications of nuclear explosives would not be amenable to routine assessment and would require assessment on an individual project basis. Because of this and the absence of experience as a basis, no attempt was made to assess these potential sources of environmental radioactivity. They should be included in future reviews and projections as sufficient information becomes available.

Experimental activities in this area are included in II. E below, since they are mostly Government activities with joint industrial participation in gas stimulation experiments.

D. Nuclear Electric Power

The nuclear electric power industry has grown rapidly during the last decade and is expected to grow considerably by the year 2000. The various facilities involved in the production of nuclear power are potential sources of environmental radioactivity. These facilities will be discussed along with estimates of radiation doses. Also included is a discussion of worldwide ^{3}H and ^{85}Kr accumulation from all sources.

1. Nuclear Electric Power Supply Requirements

Estimates have been made of worldwide nuclear electric power requirements. These were used as a basis for estimates of worldwide radiation doses from the nuclear power industry. A special government study was made for the United States requirements up to 1990.[43] That study was used as a basis for the current study and projected to 2000 at the same rate as before 1990 based on recent estimates of power requirements.[44] These are summarized below.

The world nuclear generating capacity was predicted to increase from about 20 to 2,000 billion watts electric[45] (GWE) between 1970 and 2000 (see Figure II-4). The generation of this power will give rise to radioactive effluents which will be spread worldwide. These must be considered in addition to local radiation doses in the vicinity of nuclear power plants.

The projections for the United States were made for each of the six National Power Survey Regions (see Figure II-5). These provide a basis for projecting results from past and current experience on a realistic basis. These projections are shown in Table II-9 and Figure II-4. The predictions indicated that no plants in the future would have generating capacities under 500 million watts electric (MWE) and the largest would approach 10 GWE. It should be noted that plants generally will be multiple-reactor units rather than a single reactor.

As of December 31, 1970, there were 20 operable power reactors; 51 under construction and 36 planned (reactors ordered), all of which would

Table II-9

Estimated Nuclear Generating Plant Sites - 1990[43]

	Nuclear Plants by Capacity (megawatts electric)				
Region*	500-1000	1000-2000	2000-4000	>4000	Total
Northeast	7	19	17	2	45
Southeast	10	22	21	7	60
East Central	1	10	8	2	21
South Central	3	9	9	1	22
West Central	3	6	9	1	19
West	4	7	9	13	33
TOTAL	28	73	73	26	200

*See Figure II-5.

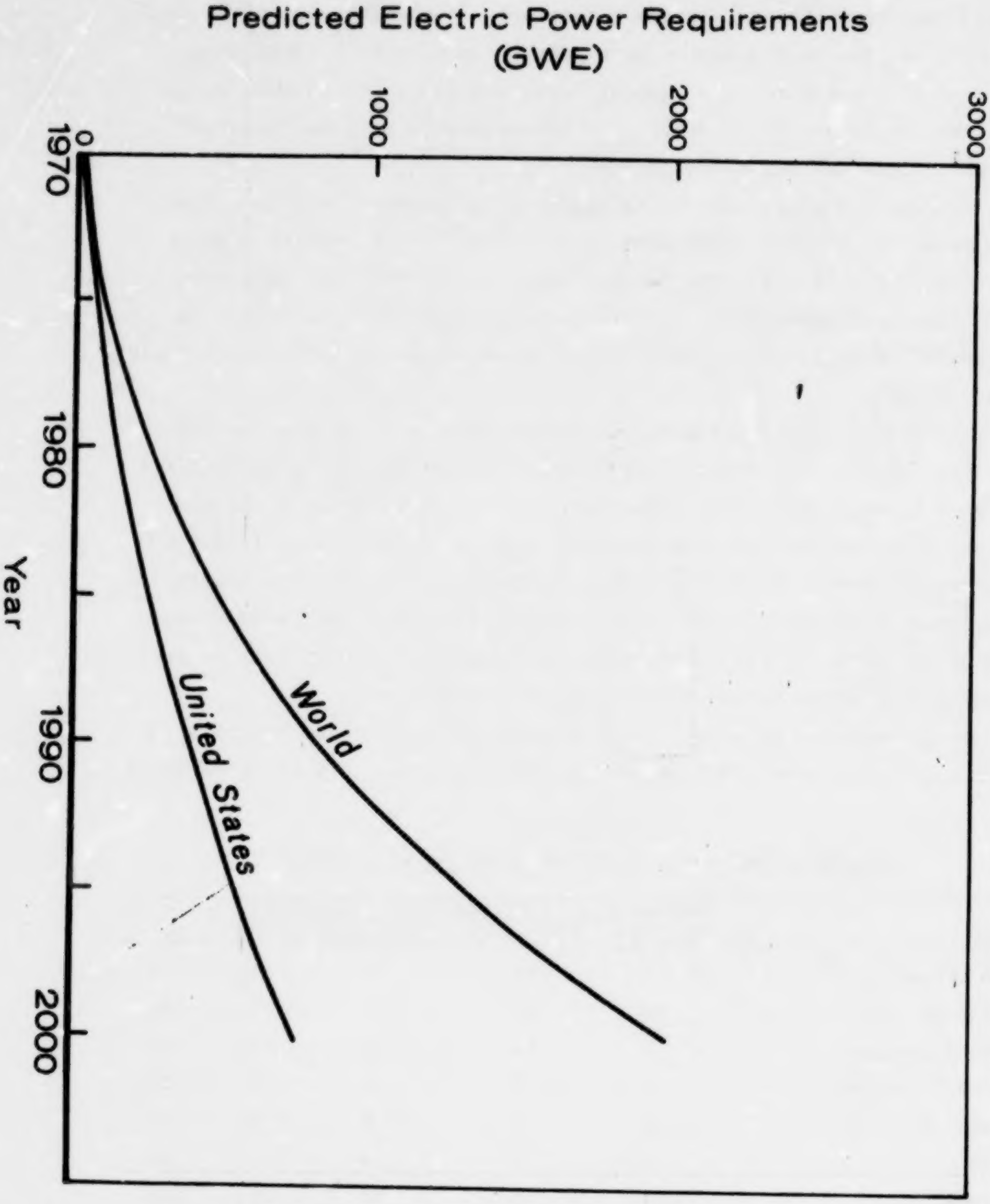
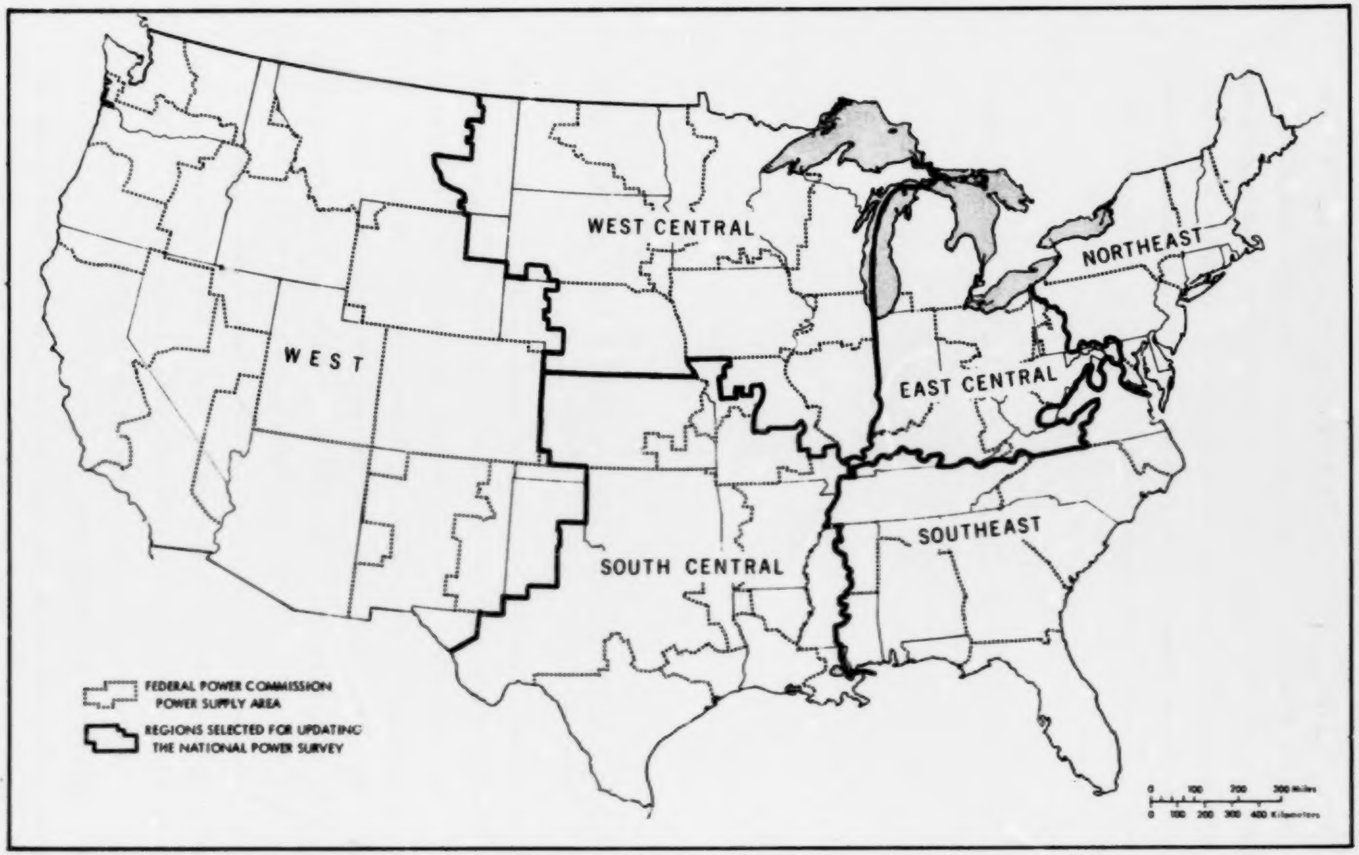


Figure II-4. Predicted World and United States Nuclear Electric Power Requirements (Adapted from References 44 and 45).



WEST CENTRAL
NORTHEAST
WEST
EAST CENTRAL
SOUTHEAST
SOUTH CENTRAL
FEDERAL POWER COMMISSION POWER SUPPLY AREA
REGIONS SELECTED FOR UPDATING THE NATIONAL POWER SURVEY
0 100 200 300 Miles
0 100 200 300 400 Kilometers

Figure II-5. National Electric Power Survey Regions.[43]

begin operation by 1979.[40] These would have a total capacity of about 95 GWE and would be located at 72 plant sites. The reactors planned to be in operation in 1975 were assumed to meet power requirements up to that time. Additional reactors were projected for these sites or additional sites in increments from 1980 to 1990 to meet predictions shown in Table II-9 for the current study. These are summarized in Table II-10.

Table II-10

Estimated Number of Operating Reactor Plant Sites by Year and Region

Year	Region						
	NE	SE	EC	SC	WC	W	Total
1960	1	0	0	0	1	0	2
1965	3	0	2	0	1	1	5
1970*	9(8)	1(1)	3(3)	0	5(4)	3(3)	21(19)
1975	20	13	8	1	13	8	63
1980	24	16	9	3	13	15	73
1985	33	38	15	13	18	24	141
1990	45	60	21	22	19	33	200

*In parentheses are numbers of sites actually in or beginning operation; delays prevented operation of other plants.

Estimates of requirements for uranium oxide indicate that uranium mining and milling would increase by a factor of about 25 between 1970 and 2000.[46,47] In 1960 there were 703 operating underground uranium mines and 166 open pit mines.[48] The numbers decreased in 1961 to 497 and 122, respectively. In 1966, there were 533 and 88. By 1972 there will be 21 uranium mills in operation.[40] In 1970 there were 10 fuel fabrication facilities. These facilities or additional ones are expected to increase production by a factor of about 15 by the year 2000. One commercial fuel reprocessing plant began operation in 1966. Two additional plants are planned to begin operation in 1971 and 1974, respectively.[40] There are expected to be about 15 plants in operation by 2000.[47]

2. Estimated Radiation Doses

Estimated radiation doses for the various types of facilities involved in the production of nuclear power are discussed below.

a. Uranium Mines

It does not appear that uranium mining activities result in significant increases in environmental radioactivity outside the immediate vicinity of mines. Measurements in mining communities and areas are in the same general range as non-mining areas.[14,15] While mining activities undoubtedly increase surface uranium and its decay products, especially radon, they are not widespread and are accounted for in general natural radioactivity measurements and estimates (see II. A above). Therefore, no additional population dose estimates were made for this activity except for occupational doses.

b. Uranium Mills

In the processing of uranium ore to extract uranium, the byproducts or tailings and waste constitute a source of radioactivity in the environment. The general practice is to pile tailings in the vicinity of the mill. The radioactive materials of significance are primarily ^{226}Ra, and its decay products, principally ^{222}Rn. Except for the possible transport of ^{222}Rn, it would be expected that, in general, no significant radioactive material would reach populated areas. Studies have been made at active and inactive mill sites with covered and uncovered tailings.[49] These studies indicated that there was no significant radiation exposure to the public from these sources. Except for stations directly over the tailings piles, radon concentrations and external gamma radiation exposures were at normal background (see II.A above).

Population doses attributable to the uranium milling industry are expected to be relatively low. The location of mills in very remote and sparsely populated areas and liquid waste treatment programs, as well as the discharge of liquid wastes to receiving waters that are not usually used for recreation or public water supplies, would support this expectation.

Instances have been reported of contamination of streams near mills through seepage from solution storage ponds[50] and discharge of effluents into streams.[50,51] In the former, dissolved radioactivity was found to be at background concentrations 1.5 mi. downstream from the mill and the water was not used for substantial distances farther downstream. In the second instance, the study resulted in a change of procedures by 1960 which reduced the discharge. These examples are typical of such situations.

While uranium milling activities contribute to the content of radioactive material in the environment, it appears from available measurements that population doses from this source cannot be distinguished from background. Therefore, no additional doses were included for uranium milling except for occupational doses.

c. Fabrication Plants

For economic as well as safety reasons, fuel fabrication plants are designed in such a manner that reactor fuel is conserved to a very high degree. It is unlikely that this activity would increase levels of exposure in the general environment. Similar activities at government facilities discussed below contribute no significant population doses. Therefore, only occupational doses are considered for fuel fabrication.

d. Nuclear Power Plants

As part of studies of the long-range requirements and impacts of the nuclear power industry, computer models were developed to assess radiation doses from reactor effluents.[52,53] These models were tested with measurements made at 13 operating reactor sites. They were used to calculate radiation doses in the current study along with the basic previously discussed.

The principal radionuclides in reactor effluents are ^{3}H, ^{58}Co, ^{60}Co, ^{85}Kr, ^{89}Sr, ^{90}Sr, ^{131}I, ^{131}Xe, ^{133}Xe, ^{134}Cs, ^{137}Cs, and ^{140}Ba. The amounts released as gaseous or liquid effluents depend on the type of reactor, and for a given type of reactor, the effluents vary widely because of the individual designs. Except for ^{85}Kr, ^{131}Xe, and ^{133}Xe, these radionuclides give rise to environmental contamination leading to potential internal doses. Krypton-85, ^{131}Xe, and ^{133}Xe emitted in gaseous effluents are the major contributors to external gamma doses as a result of immersion rather than surface deposition.

(1) External Radiation

The external radiation dose model was designed to predict doses within several radii of a reactor site. It provides the average dose within each chosen radius, the total man-rem, and the average dose to the total exposed population.

The model involves the use of average wind data by 22.5° sectors around the reactor and the estimated population within each sector. Based on experience at 13 reactors, it was assumed that whole-body external gamma doses from atmospheric effluents were 5 mrem/yr. at site boundaries for each reactor unit. In general, actual levels were much less than this, so that dose estimates are quite conservative. Doses were calculated for populations between several radii, usually up to 50 mi., since at this distance or less, radiation doses were found to be at levels not distinguishable from background. Population estimates within each sector and radius were made for at least 2 years (e.g., 1960 and 1985) and computer calculations of doses were made.[52] From these, estimates were made for the years considered in this study by interpolation or extrapolation. This was done for each reactor site in operation or currently planned. As additional reactor units at a site became operable, simple multiples of the calculations provided estimates for each site in subsequent years.

After 1975 when currently unplanned reactors would become operable (predictions, see Table II-10), the calculated doses for the operable and planned reactors were averaged by capacity and National Power Survey Region to provide estimates up to 1990. This, in effect, assumes that the average dose, exposed population, and types of reactors in each region will be the same as that for existing or planned reactors. The prediction for 2000 was made by extrapolating from the 1960 to 1990 estimates which increased in a regular manner.

It is not expected that a significant number of liquid-metal fast-breeder reactors will be in operation by 1990, although there may be by the year 2000. Since these reactors operate with significantly lower effluents than current light water reactors,[54] the dose estimates for 1990 to 2000 may be too high. Also, other technological improvements in reactor subsystems would reduce doses below those estimated. Because of the uncertainties in the availability of advanced reactor or component designs, no attempt was made to assess their effect on dose estimates.

The numerical guides proposed by the Atomic Energy Commission[55] would require employment of radiological waste systems which would reduce radiation doses. However, the assumptions used in calculations for this report are quite similar to those which would be used based on the proposed guides, as application of new guides will probably have little effect on doses.

The estimated external gamma whole-body doses are shown in Table II-11. Skin doses are estimated to be about 10 times the whole-body dose (see e below).

(2) Internal Radiation

Because of the very low levels of radionuclides in power reactor effluents even at the boundaries of plant sites, no definitive data are available to base estimates of internal doses. From limited data at a boiling water reactor,[55] an attempt was made to obtain order-of-magnitude estimates.[57] These estimates are quite conservative and maximize doses from all exposure pathways. The highest calculated dose was from ^{131}I to the thyroid from milk and drinking water. No ^{131}I was detected in milk since levels were below detection limits. Estimates based on calculations from stack release rates indicated that the highest expected levels at the nearest farm would be about tenfold less than could be measured during the study. Estimated doses from ^{131}I in drinking water were based on estimated dilution factors from a measured point to the nearest point of consumption. These were conservative as consideration was not given to decay, uptake by aquatic organisms, or adsorption. However, using these data, gross conservative estimates of time-averaged doses 360° around the reactor site indicated that they would be orders of magnitude lower than those in Table II-11. When applied to all reactors, the total man-rem would be too low to affect totals of average radiation doses.

e. Fuel Reprocessing Plants

Nuclear fuel reprocessing is another part of the nuclear electric power generating process which is a source of environmental radioactivity. In this section, estimates are made of doses accrued per year to the whole body, skin, lung, bone, thyroid, and respiratory lymph nodes

Table II-11

Estimated External Gamma Whole-body Doses from Reactor Gaseous Effluents

Year	Man-years* at Risk (millions)	Total U.S. Population (millions)	Percent of U.S. Population at Risk	Annual Man-rem	Annual Average Dose to Population at Risk (mrem/person)	Annual Average Dose to U.S. Population (mrem/person)
1960	1.9	183	1.5	16.4	0.0085	0.0001
1970	47.6	205	22.3	430	0.0091	0.002
1980	275	237	100	6,080	0.026	0.026
1990	367	277	100	22,780	0.082	0.082
2000	670	321	100	56,000	0.17	0.17

*By 1980, a significant population would reside within 50 miles of more than one reactor site, indicated by the man-years/total U.S. population.

due to exposure to radioactive material in the environment resulting from fuel reprocessing operations. Local effects to a radius of 100 km (62 mi.) around a plant are considered. Dose estimates from the nationwide buildup of ^{3}H and ^{85}Kr are considered in Section II.D.3. Since there is only one commercial fuel reprocessing plant (Nuclear Fuel Services in New York State) in operation at the present time and since its operation is not considered typical of future plants,[44] the dose values are calculated estimates and are not based on measurements.

The calculated values depend on certain assumptions made and on values selected for various factors in the dose estimations. Therefore, they depend on the validity of these assumptions and selected values. The calculated dose values will vary by as much as factors of 10 to 100 by changing the assumptions and selected values. Therefore, the methods of arriving at the dose values will be presented so that future changes can be made as more accurate information becomes available.

Only exposure to radiation from radioactive material released from the stack of a fuel reprocessing plant is considered since future plants are expected to have little radioactivity, if any, in liquid effluent.[44] Exposure pathways considered are external gamma exposures from the plume and from ground surface deposition, inhalation and skin exposure from the plume, and exposure through ingestion after surface deposition. All doses at a point a given distance from the reprocessing plant are assumed proportional to the air concentration of radioactive material at that point. Therefore, air concentrations of radionuclides are calculated and from these, dose estimates are made.

(1) Air Concentration

The air concentration at a certain location depends on the amount of fuel processed per unit time, the amount of radioactivity of the various nuclides in the fuel, the release rates of the various radionuclides, and the dilution from the stack outlet to the location. (Reference 44 was heavily relied upon to supply many of the factors needed.)

Two types of fuel are considered in the calculations - light water reactor (LWR) fuel and fast breeder reactor (FBR) fuel. Light water reactor fuel consists of uranium or plutonium while FBR fuel contains only plutonium. For this study the LWR-Pu fuel has been added with the FBR fuel since the amount of radioactivity produced per equal burnup is about the same. Table II-12 gives a projection of the amount of each type of fuel to be processed up to the year 2000.

Table II-12

Projected Quantity of Reprocessed Fuel[a]
(metric tons/yr.)

Year	Total	Reactor Fuel Type Lightwater U[b]	 Pu[c]	 Fast Breeder Pu[c]
1970	200	200	-	-
1980	3,500	2,800	700	-
1990	10,000	3,000	4,000	3,000
2000	20,000	3,000	3,000	14,000

[a] Based on:
33,000 MWd burnup/metric ton,
0.30 thermal efficiency,
0.85 load factor,
MWE capacity 2 years before processing, and
fuel mixtures from Reference 44.

[b] Treated as LWR fuel.

[c] Treated as FBR fuel.

All fuel is assumed to be irradiated to a burnup of 33,000 MW-days/metric ton with a thermal efficiency of 0.30. The LWR fuel is allowed to decay for 150 days before processing, and the FBR fuel is allowed to decay only 30 days because of the economics involved in plutonium recovery.[44] This difference in decay time causes a large difference in the amount of radioactivity present at fuel reprocessing time. Table II-13 gives the radionuclide content of the fuel at the start of reprocessing.

Most of the radioactive material will go to waste storage but there will always be some fraction released depending on the element and process involved. In Table II-14 are shown the assumed fractional releases used in this study. All ^{3}H and ^{85}Kr is released through the

Table II-13

Radionuclide Content of LWR Fuel Decayed 150 Days and FBR Fuel Decayed 30 Days*

	Concentration (Ci/metric ton)	
Nuclide	In LWR Fuel	In FBR Fuel
$^{3}\mathrm{H}$	692	932
$^{85}\mathrm{Kr}$	11,200	10,200
$^{89}\mathrm{Sr}$	96,000	637,000
$^{90}\mathrm{Sr}$	76,600	43,400
$^{90}\mathrm{Y}$	76,600	43,500
$^{91}\mathrm{Y}$	159,000	921,000
$^{95}\mathrm{Zr}$	276,000	2,100,000
$^{95}\mathrm{Nb}$	518,000	2,660,000
$^{99}\mathrm{Mo}$	—	1,810
$^{99m}\mathrm{Tc}$	—	1,730
$^{99}\mathrm{Tc}$	14.2	14.9
$^{103}\mathrm{Ru}$	89,100	1,760,000
$^{106}\mathrm{Ru}$	410,000	1,290,000
$^{103m}\mathrm{Rh}$	89,100	1,760,000
$^{111}\mathrm{Ag}$	—	12,600
$^{115m}\mathrm{Cd}$	44.3	269
$^{124}\mathrm{Sb}$	86.3	76.7
$^{125}\mathrm{Sn}$	20.0	6,720
$^{125}\mathrm{Sb}$	8,130	19,600
$^{125m}\mathrm{Te}$	3,280	6,860
$^{127m}\mathrm{Te}$	6,180	61,100
$^{127}\mathrm{Te}$	6,110	61,800
$^{129m}\mathrm{Te}$	6,690	181,000
$^{129}\mathrm{Te}$	4,290	116,000
$^{132}\mathrm{Te}$	—	4,170
$^{129}\mathrm{I}$	0.038	0.053
$^{131}\mathrm{I}$	2.17	139,000
$^{132}\mathrm{I}$	—	4,300
$^{133}\mathrm{Xe}$	—	74,400
$^{134}\mathrm{Cs}$	213,000	29,000
$^{136}\mathrm{Cs}$	20.8	28,800
$^{137}\mathrm{Cs}$	106,000	109,000
$^{140}\mathrm{Ba}$	430	523,000
$^{140}\mathrm{La}$	495	601,000
$^{141}\mathrm{Ce}$	56,700	1,480,000
$^{144}\mathrm{Ce}$	770,000	1,280,000
$^{143}\mathrm{Pr}$	694	644,000
$^{144}\mathrm{Pr}$	770,000	1,280,000
$^{147}\mathrm{Nd}$	51.0	185,000
$^{147}\mathrm{Pm}$	99,400	353,000
$^{149}\mathrm{Pm}$	—	61.5
$^{151}\mathrm{Sm}$	1,150	4,690
$^{152}\mathrm{Eu}$	11.5	10.5
$^{155}\mathrm{Eu}$	6,370	79,400
$^{160}\mathrm{Tb}$	300	9,460
$^{239}\mathrm{Np}$	17.4	7,220
$^{238}\mathrm{Pu}$	2,810	11,200
$^{239}\mathrm{Pu}$	330	3,530
$^{240}\mathrm{Pu}$	478	4,260
$^{241}\mathrm{Pu}$	115,000	600,000
$^{241}\mathrm{Am}$	200	1,570
$^{242}\mathrm{Cm}$	15,000	65,500
$^{244}\mathrm{Cm}$	2,490	1,240

*Reference 44, p. 8-14.

stack while ^{133}Xe decays considerably because of holdup in the process. The halogen and particulate release rates are values that are assumed can be attained with advanced technology. The particulate release rate depends on the off-gas flow rate and on plant size, but the values given are used for all plants in this study.

Table II-14

Estimated Fractional Release of Radionuclides Present at Time of Reprocessing*

Radionuclides	LWR Fuel Reprocessing Plant	FBR Fuel Reprocessing Plant
^{85}Kr	1.0	1.0
^{133}Xe	0.1	0.1
Tritium	1.0	1.0
Halogens	0.001	10^{-7}
Particulates	1.2×10^{-8}	8.5×10^{-10}

*Adapted from Reference 44, p. 8-12.

A concentration factor of 5×10^{-7} (μCi/cm^3)/(Ci/sec. released) was applied at a distance of 3,000 m from the plant stack. This value was selected after comparison of values given for several Atomic Energy Commission laboratories.[44,58] The ratios of the concentration factor at other distances to that at 3,000 m are given in Table II-15.

The average annual air concentration for individual or groups of radionuclides was then calculated by using the product of the radioactivity per metric ton (Table II-13), the release fraction (Table II-14), the concentration factor (5×10^{-7}), and a time factor assuming 1 metric ton per day plant capacity is equivalent to 300 metric tons processed per year.

(2) Dose Calculations at 3,000 Meters

Doses at 3,000 m from a fuel reprocessing plant to the whole body, skin, lung, bone, thyroid, and respiratory lymph nodes were calculated from the air concentrations. Whole-body gamma dose rates from most radionuclides in the plume were calculated using the following equation:

$$\frac{D(\text{nuclide i})}{D(^{137}\text{Cs})} = \frac{\Gamma_i C_i}{\Gamma_{Cs} C_{Cs}}$$

where C is the air radionuclide concentration in μCi/cm^3 and Γ is the gamma exposure rate constant for the radionuclides being considered. Its units are (R-cm^2)/(hr.-mCi). (See Appendix II-B for greater detail.) Values of Γ were calculated for each radionuclide using Γ values for a specific gamma ray energy[59] and the number of gamma rays emitted per decay.[60] The ^{137}Cs dose was taken from a detailed calculation made for the Hanford, Washington, area.[58] Krypton-85 dose values were taken from an extensive calculation[61] that gives a whole-body dose (from gamma energy) of 7 mrem/yr. for an air concentration of 3×10^{-7} μCi/cm^3. Results of these calculations are shown in Table II-16.

Table II-15

Air Concentration Distance Correction Factors[a]

Distance (m)	Air Concentration Correction Factor[b]
1,000	10.0
3,000	1.0
5,000	0.50
10,000	0.20
50,000	0.026
100,000	0.010

[a] Adapted from References 44 and 58.

[b] $\text{Factor} = \frac{\text{Air concentration at selected distance}}{\text{Air concentration at 3,000 m}}$

Whole-body gamma dose rates from radioactive material deposited on the ground were determined by two methods. For the noble gases, calculations of others[44] were used for ^{85}Kr, and ^{133}Xe was compared to ^{85}Kr by the use of the Γ factor. All other nuclides were compared to calculated values for ^{131}I and ^{137}Cs using calculations for Hanford.[58] The nuclides were divided into two groups according to half-life since the half-life affects the maximum buildup on the ground. Those with a half-

Table II-16

Estimated Annual Dose Accrued at 3,000 Meters from a Fuel Reprocessing Plant per 300 Metric Tons of Fuel Reprocessed per Year

Exposure Pathway		Body Organ[a]	Annual Dose Accrued (mrem/person at 3,000 m)	
			LWR Fuel	FBR Fuel
A.	External gamma from plume passage			
	1. ^{85}Kr	Whole body	1.2	1.1
	2. ^{133}Xe	Whole body	-	9.1
	3. All other nuclides	Whole body	$<10^{-3}$	$<10^{-3}$
B.	External gamma from surface deposition			
	1. ^{85}Kr	Whole body	0.09	0.08
	2. ^{133}Xe	Whole body	-	0.6
	3. All other nuclides	Whole body	~0.04	~0.02
C.	Inhalation and skin dose from plume passage			
	1. ^{3}H	Whole body	5.0	6.7
		Skin	0.2	0.2
	2. ^{85}Kr	Lung	0.9	0.8
		Skin[b]	53	48
	3. ^{133}Xe	Lung	-	0.3
		Skin[b]	-	5.7
	4. ^{144}Ce	Lung	0.3	0.04
		Bone	0.4	0.05
	5. ^{131}I	Thyroid	0.1	0.7
	6. ^{129}I	Thyroid	0.01	$<10^{-5}$
	7. ^{90}Sr	Bone[c]	0.02	0.0009
	8. Pu	Bone[c]	0.6	0.2
		Lung[c]	0.9	0.3
		Respiratory[c] lymph nodes (RLN)	310.0	110.0

(continued)

Table II-16 - continued

Exposure Pathway	Body Organ[a]	Annual Dose Accrued (mrem/person at 3,000 m)	
		LWR Fuel	FBR Fuel
9. Other actinides (^{241}Am, ^{242}Cm, ^{244}Cm)	Bone[c]	0.2	0.03
	Lung[c]	0.8	0.2
	RLN	100	20
10. All others	Lung	~0.2	~0.1
D. Ingestion from surface deposition			
1. ^{89}Sr	Bone[c]	0.008	0.004
2. ^{90}Sr	Bone[c]	0.14	0.006
3. ^{129}I	Thyroid	11.2	0.002
4. ^{131}I	Thyroid	13.0	82
5. ^{137}Cs	Whole body	0.02	0.001

[a] Doses to organs other than the whole body are in addition to whole-body doses.

[b] At 0.07 mm depth.

[c] These doses received over 50 years following exposure (see Section II.B.2). All other doses received within 1 year of exposure.

life less than 1 year were compared with ^{131}I and those with a half-life greater than 1 year were compared with ^{137}Cs. A ^{137}Cs buildup for 1 year was used. Assuming that ground deposition is proportional to air concentration, the dose rates were calculated using the Γ values and the ^{131}I and ^{137}Cs data from Hanford. A body shielding factor[31] of 0.82 and a structural shielding factor[30] of 0.4 were applied to correct air dose rates to body dose rates. The results are presented in Table II-16, Part B.

Skin doses and doses caused by inhalation of radioactive material from the plume are given in Table II-16, Part C. The equations used in calculating these doses are given in Appendix II-B.

Estimated doses from ingestion of radionuclides due to surface deposition were based on calculations made for the Dresden Nuclear Power

Station.[57] The Dresden dose values (see Appendix II-B) were corrected to correspond to the assumed release rates from a fuel reprocessing plant. Exposure pathways considered were:

(a) atmospheric discharge → deposition on grass → cattle → milk → man,

(b) atmospheric discharge → deposition on leafy vegetables → man, and

(c) atmospheric discharge → deposition on grass → cattle beef → man.

The results are presented in Table II-16, Part D.

A summary of Table II-16 is given in Table II-17 showing annual accrued doses to the whole body, skin, lung, bone, thyroid, and respiratory lymph nodes at 3,000 m from a plant processing 300 metric tons of fuel per year. Each of the individual organ doses also contains the whole body dose. Dose values at other distances can be obtained by using the correction factors in Table II-15.

Table II-17

Summary of Table II-16

Estimated Annual Dose Accrued at 3,000 Meters from 300 Metric Tons of Fuel Reprocessed per Year

Body Organ	mrem/person at 3,000 m LWR Fuel	 FBR Fuel
Whole body	6.3	18
Skin[a,b]	60	72
Lung[b,c]	9.4	20
Bone[b,c]	7.7	18
Thyroid[b]	31	100
Respiratory lymph nodes[b,c]	420	150

[a] At 0.07 mm depth.

[b] Includes whole-body dose.

[c] Respiratory lymph node dose and a small portion of the bone and lung dose are received over the 50 years following exposure. Other doses are received within 1 year of exposure.

(3) Average Population Dose

The average annual dose accrued per person for the population around a reprocessing plant (out to a distance of 100 km) was determined using an average value of dose calculated for a specified population distribution.[62] If the population density is uniform to a radius of 100 km around the plant, the average per capita dose for a specified dose at 3,000 m is 0.027 times the dose at 3,000 m. If the population density increases at a constant rate as the distance from the plant increases, the average dose factor is 0.015. The first value was chosen for this study. Applying it to the values in Table II-17, Table II-18 was obtained which gives annually accrued per capita dose within 100 km per 300 metric tons of fuel processed per year.

Table II-18

Average Annual Dose Accrued to the Population

Within 100 Kilometers of a Fuel Reprocessing Plant

(per 300 metric tons processed per yr.)

	Accrued Dose (mrem/person/yr.)	
Body Organ[a]	LWR Fuel	FBR Fuel
Whole body	0.17	0.49
Skin	1.6	1.9
Lung	0.25	0.54
Bone[b]	0.21	0.49
Thyroid	0.84	2.7
Respiratory lymph nodes[b]	11	4.0

[a] Individual organ doses include whole-body doses.

[b] Respiratory lymph node and part of bone doses received over the 50 years following exposure.

Total man-rem was calculated by assuming a number for the population living within 100 km of the processing plant; 1.5×10^6 was chosen as the population value for 1970 and a 16% increase per decade was used. This value is reasonably representative of currently operating reactors, and the rate of population increase is the same as for the United States population (Table II-11). From these population values and the projected annual quantity of reprocessed fuel in Table II-12 the annual per capita dose was calculated for the various body organs. The results are given in Table II-19.

The 1970 dose estimates were based on assumptions used in this study. However, Nuclear Fuel Services' (NFS) operations are different than assumed operations of the future.[44,63-65] A major difference is that much of the waste effluent is through water media rather than entirely through the air. Data from around NFS are not conclusive as far as population doses are concerned. Calculated doses to a "typical individual"[63] based on these data are so close to fallout background that it cannot be determined what portion of the dose is from fuel reprocessing. The most significant doses are those resulting from activities involving the stream containing liquid effluent waste. The ingestion of fish and game from sport fishing and hunting provides the largest potential exposure. The measured and calculated air concentration factor[64] at 3,000 m is about 200 times less than the value used in this study. Therefore, air pathway doses are expected to be much less than those given in Tables II-16 to II-19. The additional doses from the water pathways will keep the total man-rem in the range of 100 to 200, however.

(4) Discussion

It must be recognized that modification of these calculations is possible. Release rates will depend on the technology used at each plant, concentration factors will vary from location to location, population distributions will vary, and methods of dose calculation will change as new data are obtained. Therefore, the values in Table II-19 may vary by as much as a factor of 10 or more. The values in this section do show, however, which radionuclides result in the greatest dose.

3. Worldwide Radioactivity

Two radionuclides are of concern on a worldwide scale. Because of their chemical and physical properties, many separate sources of these radionuclides may cause a general buildup of their concentration in the biosphere. Tritium is distributed throughout the surface waters

Table II-19

Estimated Annual Dose Accrued to the United States Population from Fuel Reprocessing

Year	Whole-body Dose (mrem/person)	Man-rem to U.S. Population	Other Body Organ Doses (mrem/person)				
			Skin	Lung	Respiratory Lymph Nodes*	Bone*	Thyroid
1970	0.0008	170	0.008	0.001	0.05	0.001	0.001
1980	0.02	5,000	0.1	0.03	0.8	0.02	0.1
1990	0.09	25,000	0.4	0.1	1.4	0.09	0.5
2000	0.2	65,000	0.8	0.2	2.3	0.2	1.1

*Dose received over 50 years following exposure.

of the world and is of concern to man through any exposure pathway involving water. Krypton-85, a noble gas, is distributed throughout the atmosphere and is a source of exposure to man, both externally and through inhalation. All sources of these radionuclides will be considered in this section.

a. Tritium

Tritium is produced naturally by cosmic rays and artificially by thermonuclear detonations and in nuclear electric power production. It contributes only to internal doses because of its low beta decay energy. The worldwide content of ^3H from all sources is projected and from this the dose is estimated.

(1) Natural ^3H

The sources of natural ^3H are cosmic ray bombardment of oxygen and nitrogen in the upper atmosphere and direct intrusion from outer space.[2] Estimates of the worldwide inventory of naturally produced ^3H have been graphically summarized.[66] The range of most probable values is shown in Figure II-6 and varies from 25 to 80 MCi.

(2) Nuclear Explosives

Both the fission and fusion processes of nuclear explosives produce ^3H. The fission process produces 1,000 to 2,000 Ci of tritium per megaton (MT) of fission energy which is negligible compared to the 6 to 10 MCi produced per megaton of fusion energy.[66,67] The ^3H produced by weapon detonations and corrected for decay through 1962 was calculated using the 6 to 10 MCi/MT of fusion energy and the atmospheric fusion yield detonated over certain time periods.[27] Tritium from underground detonations is assumed to be contained near the detonation site and is of no worldwide consequence. The ^3H accumulated to 1962 was corrected for decay to the year 2000 as shown in Figure II-6. Figure II-6 also shows the world inventory if 20 MCi per year or 100 MCi/yr. is added by nuclear detonations. Since 1965, less than 20 MCi of ^3H per year[68] have probably been added by French and Chinese tests.

(3) Reactors

Tritium is produced in reactors by several methods. The most important of these methods are in the fission process itself and by neutron

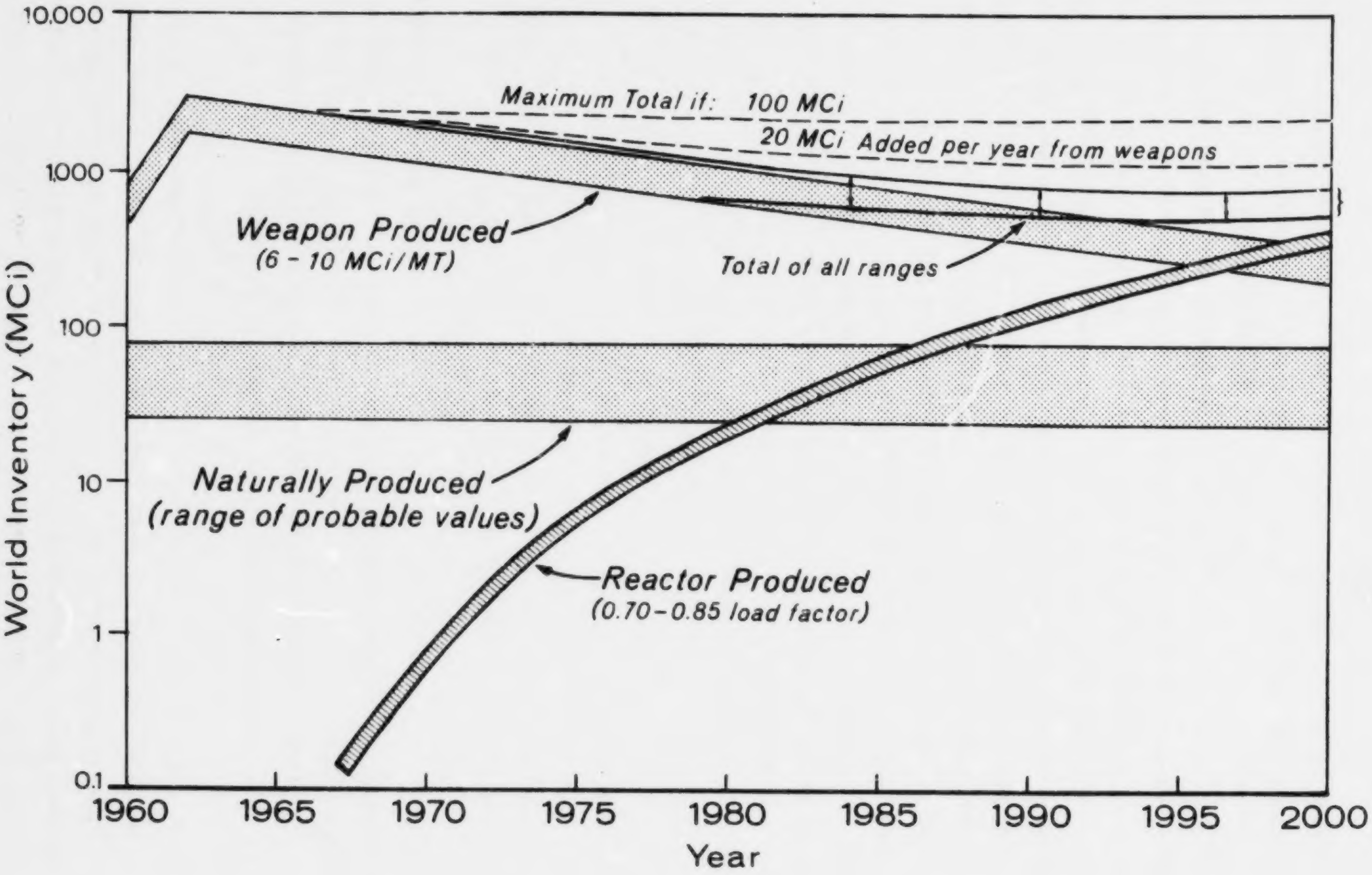


Figure II-6. Estimated World Inventory of Tritium in the Atmosphere and in Surface Waters.

interactions with boron in reactor control rods, with boron and lithium in the primary reactor coolant, and with deuterium in heavy water (D_2O) reactors.[66,69] For this study, it was assumed that (a) all ^{3}H produced by the fission process corrected for 1 year of decay will be lost to the environment either at the reactor site or during fuel reprocessing, (b) that ^{3}H produced in control rods will not be released to the environment, (c) that technological changes will reduce ^{3}H production in the coolant to a negligible level, and (d) that 5% of the world's production of nuclear power will be by D_2O reactors. A D_2O reactor is assumed to contain 430 kg of D_2O coolant per MWE with a ^{3}H concentration of 11 Ci/kg with 2.5% being lost per year to the environment.[69]

Table II-20

Projected World Reactor Power Capacity
(GWE)

Year	Total World* Reactor Power	D_2O Reactors	U-fueled Reactors	Pu-fueled Reactors
1970	20	1	19	0
1980	250	12	200	38
1990	800	40	240	520
2000	2,000	100	240	1,660

*Total world power values are taken from Reference 45, as reasonable values when compared to the projected power capacity of the United States.

Total world nuclear power capacity is projected in Table II-20. Five percent is allotted to D_2O reactors with uranium fuel and the remainder is divided between uranium- and plutonium-fueled reactors in the same ratios as used in Table II-12. The fuel types are separated because uranium fuel produces 19 Ci ^{3}H/MWE/yr. and plutonium fuel produces 36 Ci/MWE/yr.[66]

Estimated reactor ^{3}H production is shown in Figure II-6. The range of values is caused by varying the power load factor from 0.70 to 0.85. The upper value can be increased by 13% in the year 2000 if the fraction of D_2O reactors is doubled, or the lower value can be decreased by about 10% if the amount of uranium-fueled reactors is doubled and the plutonium-fueled reactors are decreased. The upper value of the range could also be increased by considering some ^3H being formed in the coolant of light water reactors. These changes would about triple the reactor range shown on the graph.

(4) Total ^3H

The maximum and minimum ranges of the three individual components of ^3H inventory have been added with the results shown in Figure II-6. This shows that if no more thermonuclear explosives are detonated above ground, the environmental ^3H level in the year 2000 will be less than half the 1970 level. Explosive-produced ^3H is predominant at the present time and will continue to be if up to 100 MCi (equivalent to 10 to 15 MT of fusion energy) are released to the environment per year. Reactor-produced ^3H will not become important on a worldwide basis until after 1990.

(5) Dose

The dose from worldwide ^3H depends on the ^3H content in food and water which will depend on the worldwide inventory. The whole-body ^3H dose rate, D, is calculated from:

$$D = 0.089X_w \text{ mrem/yr.}$$

where X_w is the average ^3H equilibrium concentration in water and diet (nCi/liter). The factor 0.089 was determined using a body tissue content of 60% water, a quality factor of 1.0, and a factor of 1.4 increase in dose due to organic labeling through chronic exposure.[70]

The X_w can be estimated in several ways. One is to divide the total world ^3H inventory by the volume of circulating surface waters. Surface water volume estimates[44,69] range from 1.4 to 2.7 x 10^{16} m^3 (depending on the depth of ocean waters used) with the volume between 30° and 50° N. equal to 0.1 of the total volume. Since most ^3H is released in the mid-latitudes of the Northern Hemisphere, it is assumed that 50% is distributed from 30° to 50° N. and 50% in the rest of the world. For the range of ^3H world inventory values in 1970, this gives a range of X_w of 0.2 to 0.7 nCi/liter.

The X_w can also be determined by direct measurement. It is found that X_w varies considerably from one location to another. Most surface and groundwater values in the United States vary from 0.2 to 1.5 nCi/liter.[71,72]

A third method of determining X_w for dose calculations is from diet studies. These show that from 1967 to 1969 the average ^3H level in the United States diet[73] was about 0.5 nCi/kg.

Therefore, 0.5 nCi/liter is considered indicative of present ^3H levels in the environment and in the diet, and future levels are predicted by the trend shown in Figure II-6 using 20 MCi/yr. of added ^3H from nuclear explosives tests. The resulting doses for the United States population are given in Table II-21.

Table II-21

Estimated Annual Whole-body Dose from Worldwide ^3H

Year	Dose (mrem/person)	Man-rem for U.S. Population
1960	0.02	3,100
1970	0.04	9,200
1980	0.03	7,100
1990	0.02	6,700
2000	0.03	8,400

b. Krypton-85

Krypton-85 is produced artificially by nuclear explosive detonations and by nuclear electric power production. Nuclear explosive production rates are very low compared to reactor production. The world inventory from nuclear explosives is calculated to be about 3 MCi. However, reactors are already producing greater than 10 MCi/yr. Therefore, only reactor production will be considered for the future. Dose estimates will be determined from air concentration values.

(1) Air Concentration

The ^{85}Kr air concentrations[74] in 1960, 1965, and 1970 were about 5, 10, and 15 pCi/m^3, respectively. Future values of concentration are calculated from reactor production rates assuming all ^{85}Kr (corrected for 1 year of decay) will be released to the atmosphere. Krypton-85 yield corrected for decay is 410 Ci/MWE/yr. for ^{235}U thermal neutron fission and 380 Ci/MWE/yr. for ^{239}Pu fast neutron fission.[44] Using fuel mixtures as used for ^{3}H in Table II-20 and a load factor of 0.85, the ^{85}Kr concentration as shown in Figure II-7 was obtained. For the lower curve it was assumed that the total ^{85}Kr is distributed uniformly in the total atmosphere[75] of 5.1×10^{21} g (air density is 0.0013 g/cm^3 at mean sea level). For the upper curve it was assumed that 75% of the ^{85}Kr is distributed in the Northern Hemisphere since this is where most of it is produced.

(2) Dose

Annual doses were calculated from air concentrations. A concentration of 3×10^5 pCi/m^3 was considered to give 7 mrem/yr. to the whole body, 310 mrem/yr. to the skin at 0.07 mm depth, and 12 mrem/yr. to the lungs.[58,60] Using these values and the upper range of air concentrations in Figure II-7, the dose values in Table II-22 were calculated. (It should be noted that in the literature, skin dose is quite often referred to as whole-body dose.)

Table II-22

Estimated Annual Doses to the United States Population from Worldwide Distribution of ^{85}Kr

	Dose			
	Whole-body		Skin	Lung
Year	(mrem/person)	(man-rem)	(mrem/person)	(mrem/person)
1960	0.0001	20	0.005	0.0002
1970	0.0004	80	0.02	0.0006
1980	0.003	700	0.1	0.005
1990	0.01	4,000	0.6	0.02
2000	0.04	12,000	1.6	0.06

E. Government Facilities

The government facilities which are potential sources of environmental radiation include many types. Those concerned with somewhat nonroutine intermittent activities are discussed separately. The Nevada Test Site (northwest of Las Vegas, Nevada) is considered as a single

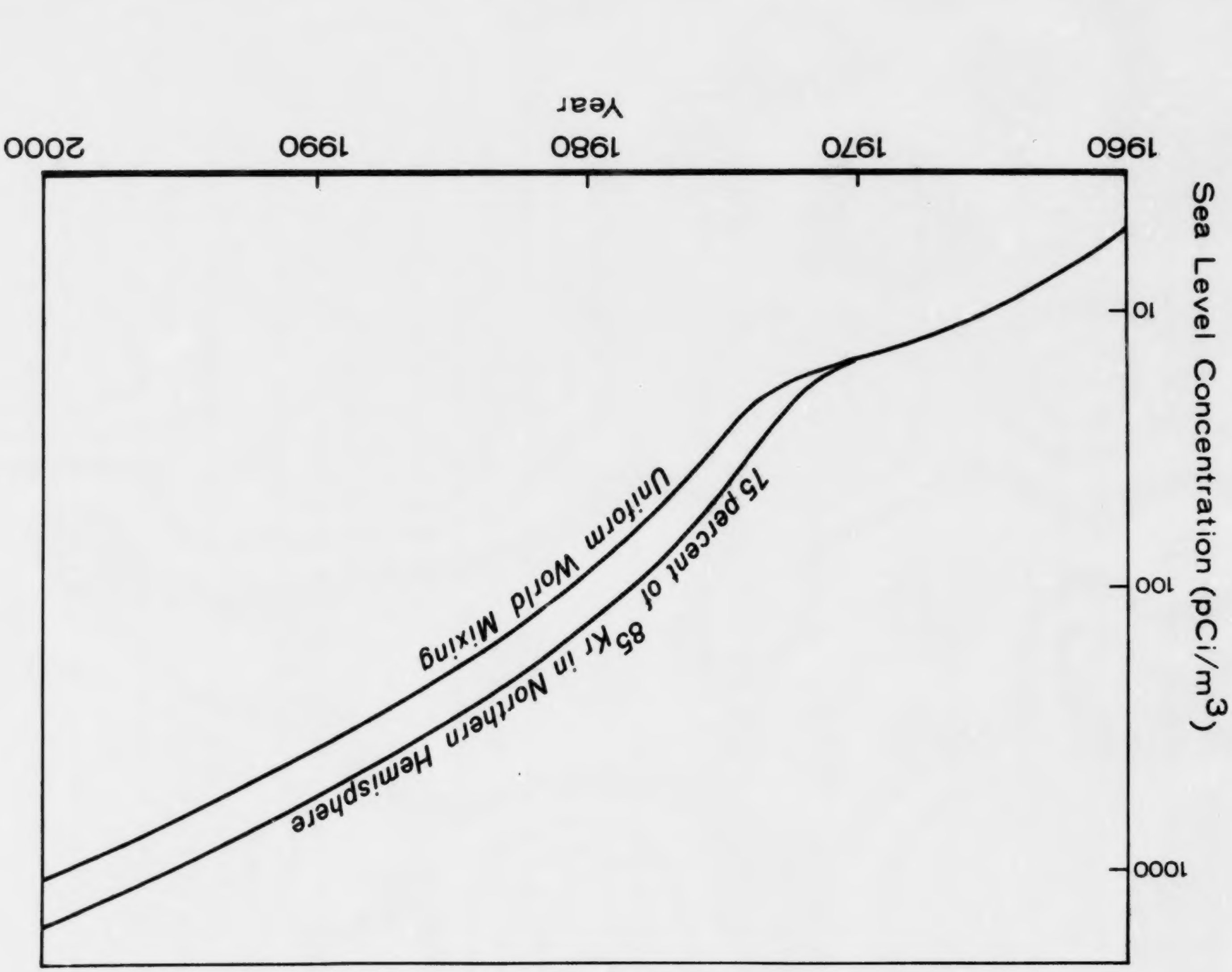


Figure II-7. Estimated ^{85}Kr Concentration in the Northern Hemisphere from Nuclear Electric Power Production.

facility although several government agencies are sponsors of some activities; both weapons and peaceful nuclear explosives tests are carried out there. Also, the Amchitka Island tests are considered as part of that facility. Peaceful nuclear explosives tests conducted off the Nevada Test Site are considered separately as are activities of the Nuclear Rocket Development Station (adjacent to the Nevada Test Site).

1. Nevada Test Site

For estimating radiation doses from activities at the Nevada Test Site for the early part of the last decade, the period from September 15, 1961 to September 15, 1962 was selected. (A similar period in 1969 and 1970 was considered.) This was the period of resumption of atmospheric nuclear explosives testing following the moratorium of 1958. During this period, attempts were made to collect more useful data for assessing radiation doses to the population in the vicinity of the Nevada Test Site than had been obtained previously. Included was a relatively extensive personnel film badge program giving measurements of actual external gamma radiation exposures to members of the potentially exposed offsite population.[75] Also, measurements were obtained providing a basis for estimating internal doses. These were in addition to ground monitoring and station personnel film badge data. The estimates made were based primarily on the latter and extended with supplemental data where necessary. Calculations were made for distances where doses appeared to be indistinguishable from worldwide fallout.

Two underground nuclear tests have been conducted at the test site on Amchitka Island, Alaska. No radioactivity was detected off the site following these tests.[72] Similar results are expected for future tests at that site.

Based on the available data,[75,78] arithmetic average doses were calculated for each community. Then, estimates of average external gamma doses were made for each of the smallest census divisions in the region of interest. From these, the total man-rem were calculated. During the period from September 15, 1961 to September 15, 1962, the calculated average whole-body dose was 47 mrem to the exposed population of 18,000 persons, or 860 man-rem. Since the calculations were based on personnel film badge measurements and the sources were primarily atmospheric volume sources, the shielding and screening factors for conversion to doses were assumed to be unity.

During a similar period 1969 to 1970, there were no Nevada Test Site activities which caused doses to the population in the vicinity of the installation. Future doses from this source are unpredictable. Sufficient data are not available on possible peaceful nuclear excavation tests to provide a basis for predictions and each would require separate predictions based on specific characteristics. Other nuclear tests' radioactivities would be completely contained underground except for unforeseeable conditions.

Using levels of radionuclides in milk,[75,79,80] estimates of internal doses were made using the methods described in II. B. The data were adjusted so that the doses were contributed by only local fallout from the Nevada Test Site. However, the calculated doses here are probably overestimates, while those from worldwide fallout are probably underestimates. The region of concern generally had higher levels of worldwide fallout than the average for that section of the nation. Worldwide fallout dose calculations were considered in II. B. Only ^{131}I and ^{137}Cs appeared in milk in significant amounts over those from worldwide fallout in the same region to contribute to the estimates.

The calculated average whole-body dose from ^{137}Cs to a population of about 792,000 was 10 mrem during the period considered, or 7,920 man-rem. The average dose to the thyroid to the same population was estimated to be 9 mrem.

The total estimated whole-body dose of 8,780 man-rem to a population of 810,000 (an average of 11 mrem to the population at risk) gives 0.05 mrem/person to the total United States population for the period considered.

2. Nuclear Rocket Development Station

From 1959 through 1969, 31 nuclear reactor rocket engine tests were conducted at the Nuclear Rocket Development Station. During each of these tests, data were collected and reported for purposes of radiological assessments (e.g., References 81 to 83). Based on these data, calculations of external whole-body doses and organ doses were made and reported.[84] These were used as a basis for estimates made during this study. For this facility, doses were calculated for the entire 10-year period.

To date, external gamma doses were too low to be significant for all tests. The principle effluent radionuclides from these tests are ^{131}I and ^{133}I and concentrations were too low to give significant external gamma exposures during cloud passage or after deposition.

Levels of these nuclides were detected in milk and led to thyroid dose estimates. The average thyroid dose to a population (1960) of about 740,000 was calculated to be about 3 mrem, or 2,100 man-rem during the 10-year period.

It is not possible to predict the dates of future tests of nuclear rocket engines or possible levels of effluents. During the period considered above, the technology program was completed. The development of a flight-rated rocket engine has been initiated and some tests are required during this phase.[40] Adequate estimates of potential doses to populations in the vicinity of the test facility require individual treatment.

3. Peaceful Nuclear Explosive Tests

Peaceful nuclear explosives tests conducted at places other than the Nevada Test Site are discussed. To date, the following have been conducted:

Date	Project	Location
December 10, 1961	Gnome	near Carlsbad, New Mexico
December 10, 1967	Gasbuggy	near Farmington, New Mexico
September 10, 1969	Rulison	near Grand Valley, Colorado

All of these were underground tests. During the Gnome test, radioactivity escaped from the cavity to the environment.[85] The other two were gas stimulation tests, and no radioactivity was found off the test sites during the detonation phase.[86,87] Radioactivity was released to the environment after gas wells were drilled into the cavities to obtain experimental data. The gas was deliberately flared, thus releasing small amounts of radioactivity to the atmosphere. Because of the similarities of the Gasbuggy and Rulison events, only the former is discussed (see Reference 87). As with the above facilities and the applications discussed in C, future tests are too uncertain with respect to time, place, and type to permit adequate predictions of potential doses.

a. Project Gnome

For several hours, some venting occurred sporadically during Project Gnome shortly after the detonation.[85] The effluent was mostly gaseous and deposition was only detected about 10 mi. off the test site. Doses in populated areas were due to passage of the cloud. Calculations of external gamma doses were made from instrument readings at populated locations along the path of the cloud. These gave a total of 30 man-rem for a population of about 45,000 persons, or an average dose of 0.7 mrem. Shielding and screening factors for conversion of measurements to doses were assumed to be unity. Analyses of environmental samples indicated levels of radionuclides about the same as or lower than those for the general region. Therefore, no significant internal radiation doses resulted from this event.

b. Project Gasbuggy

During the gas production phase of this test, radioactivity was released from the well. Only ^{3}H, ^{14}C, and ^{85}Kr were detected in the effluent.[86] No radioactivity was detected beyond 10 mi. of the gas well and there are no populated sites within that distance of the well. Calculational estimates of doses for areas beyond 10 mi. of the well were not significant.

4. Other Atomic Energy Commission Facilities

Other Atomic Energy Commission facilities involve a wide variety of activities in the Atomic Energy Program and a large number of contractor activities.[40,88] Most of the major facilities operated by and for the Atomic Energy Commission involve multiple-purpose activities, although a few are concerned with only certain phases of nuclear materials production or manufacturing. Most are concerned with research in one or more areas. The majority of facilities are those of research contractors at universities, and private, commercial, and government installations.

Most of the facilities involve the use of radioactivity and constitute a source of environmental radioactivity through airborne or liquid releases of wastes. A few emit radiation inside the facility which is measurable outside the facility. The nature of the facility and its potential for contamination of the general environment determine the degree to which data are obtained to assess the impact of the facility on the environment. Facilities such as the National laboratories and similar installations generally have extensive programs of environmental surveillance of radioactivity. Those using only relatively small quantities of tracer radionuclides in research usually have a minimal surveillance program, often simply monitoring effluents before release to insure compliance with regulations.

Estimates were made for populations at risk in the vicinity of the facilities as well as for the total United States population. The years considered were those typical of the early (indicated as "1960") and latter (indicated as "1970") parts of the decade 1960 to 1970. The National Accelerator Laboratory, expected to begin operation in 1971 was also included in the "1970" estimates. It was assumed that the situation in the period 1970 to 2000 would be similar to that in "1970" although different facilities may be involved. The facilities (not considered elsewhere in this report) contributing to significant doses are among those listed in Table II-23. Included in the list are some in operation in 1960 but not in 1970 and some beginning operation after 1960. In many cases, the activities at facilities have changed considerably either by reduction or cessation of some activities or beginning or increasing others.

A large number of reports were used as a basis for the estimates made for this section.[89-101] Only the major ones contributing significantly to doses are listed in the references. The distances from facilities to which estimates were made were sufficient to include doses above about 0.01 mrem/yr. Data were extrapolated to farther distances than reported and dose calculations were made in some cases by methods described elsewhere in this report (see II. D). Where reported data probably included natural and fallout radioactivity, estimates of these were considered by methods discussed in II. A and B.

The estimated whole-body (internal and external) doses are shown in Table II-24. In most cases, external gamma radiation doses were based

Table II-23

Major Atomic Energy Commission Installations

Aircraft Nuclear Propulsion Department, Cincinnati, Ohio
Argonne National Laboratory, Argonne, Ill.
Atomics International, Canoga Park, Calif.
Bettis Atomic Power Laboratory, Pittsburgh, Pa.
Brookhaven National Laboratory, Upton, N.Y.
Cambridge Electron Accelerator, Cambridge, Mass.
Connecticut Aircraft Nuclear Engine Laboratory, Middletown, Conn.
Feed Materials Production Center, Fernald, Ohio
Feed Materials Production Facility, Weldon Spring, Mo.
Hanford Facilities, Richland, Wash
Knolls Atomic Power Laboratory, Schenectady, N.Y.
Lawrence Laboratories, Berkeley and Livermore, Calif.
Los Alamos Scientific Laboratory, Los Alamos, New Mex.
Mound Laboratory, Miamisburg, Ohio
National Accelerator Laboratory, Batavia, Ill.
National Reactor Testing Station, Idaho Falls, Idaho
Neutron Devices Department (Pinellas), St. Petersburg, Fla.
Oak Ridge Research and Development and Production Facilities, Oak Ridge, Tenn.
Paducah Plant, Paducah, Ky.
Portsmouth Gaseous Diffusion Plant, Piketon, Ohio
Princeton-Pennsylvania Accelerator, Princeton, N.J.
Rocky Flats Plant, Rocky Flats, Colo.
Sandia Laboratories, Albuquerque, New Mex.
Savannah River Facilities, Aiken, S. C.
Stanford Linear Accelerator Center, Palo Alto, Calif.

Table II-24

Estimated Total Annual Whole-body Doses from Other Atomic Energy Commission Installations

Year	Population at Risk (millions)	Percent of U.S. Population at Risk	Annual Man-rem	Average Dose to Population at Risk (mrem)	Average Dose to U.S. Population (mrem)
"1960"	2.4	1.3	2,600	1.1	0.01
"1970"	1.6	0.8	2,500	1.5	0.01
1980	1.8	0.8	2,700	1.5	0.01
1990	2.2	0.8	3,300	1.5	0.01
2000	2.5	0.8	3,800	1.5	0.01

on open field measurements. Therefore, a shielding factor[30] of 0.4 and a screening factor[31] of 0.8 were used in those cases. Internal doses to the lung, thyroid, and bone are shown in Table II-25.

Table II-25

Estimated Internal Doses[a] from Other Atomic Energy Commission Facilities

Year	Population at Risk (millions)	Annual Average Dose (mrem)
Lung		
"1960"	4.9	0.6
"1970	5.5	0.6
Thyroid		
"1960"	0.26	45[b]
"1970"	0.1	1.3
Bone		
"1960"	0.26	4.3
"1970"	0.1	4.8

[a] Do not include whole-body doses.

[b] Probably includes some fallout although an estimated fallout component was excluded from these estimates.

5. Other Government Facilities

Several other government agencies maintain facilities involving radiation and radioactivity. Included are the Department of Agriculture; Department of Defense; Department of Health, Education, and Welfare; National Bureau of Standards; Geological Survey; Environmental Protection Agency; National Aeronautics and Space Administration; and Veterans Administration. The NS Savannah began operation in 1965 by the Maritime Administration. Operation of the ship was terminated in 1971. Nuclear power stations operated by the Tennessee Valley Authority, Department of Defense and Panama Canal Company are considered in II. D. Nuclear testing activities by several government agencies are considered as part of the Atomic Energy Commission's activity in Paragraph 1 above.

A large number of government research and medical facilities utilize radionuclides and radiation sources in their activities, similar in general to such facilities operated by the Atomic Energy Commission. Several of these include research, experimental, and test reactors. In 1960 there were four of these operating at a total of about 6 MW and in 1970, there were six operating at about 2 MW. A large number of radiation sources are used for industrial-type purposes; e.g., well-logging, radiography, and luminescence.

Most of these facilities discharge some radioactivity to the environment as liquid and gaseous wastes, or use radiation sources which are potential sources of environmental radiation. None of these discharge radioactivity at levels comparable to those discussed in Section II.E.4 which contributed significant population doses. Based on estimates for some facilities and comparisons of these facilities with similar types as those above (where effluents have higher levels of radioactivity), it was concluded that these other government facilities contributed no significant doses to populations in the United States in the vicinity of these facilities, except occupational doses. Comparisons of occupational doses suggest similar conclusions as do negative environmental monitoring data (e.g., References 102 and 103).

F. Private Facilities

Many of the major private facilities utilizing radioactivity or radiation sources are involved in the nuclear electric power industry and were included in II. D above. Some others are operated under contract with Government agencies and were included in II. E above. The remainder of private facilities include research and medical organizations and those concerned with commercial applications similar to those discussed above. Others are concerned with radionuclide preparation as sources, tracers, pharmaceuticals, or radiation source devices.

The effluents from these facilities are generally of the order of magnitude or less than the government facilities discussed in II. E

Therefore, these facilities contribute no significant doses except from occupational exposures.

G. Summary

Estimated whole-body doses from environmental radiation are summarized in Table II-26. Total man-rem will increase because the population will increase as shown by the man-rem per million people remaining constant. Environmental radiation caused by the nuclear electric power production process will increase faster than the population but it is estimated to be less than 1% of natural radiation by the year 2000. Environmental radiation doses to the whole body are compared to radiation doses from other sources in Section V.

Doses to other organs of the body are given in several sections in the report. Natural internal radiation dose estimates for the bone marrow and the lung are given in Table II-3; fallout radiation doses to the lung, skin, thyroid, bone, and respiratory lymph nodes in Tables II-6 and II-7; doses to the same organs from fuel reprocessing activities in Tables II-16 to II-19; lung and skin doses from the worldwide distribution of ^{85}Kr in Table II-22; thyroid doses from activities at the Nevada Test Site and the Nuclear Rocket Development Station; and lung, bone, and thyroid doses around several Atomic Energy Commission facilities in Table II-25.

Table II-26

Summary of Estimates of Whole-body Environmental Radiation Doses to the United States Population

	Annual Man-rem (millions) for Years				
Source	1960	1970	1980	1990	2000
Natural					
Cosmic	8.2	9.2	10.7	12.5	14.4
External gamma	11.0	12.3	14.2	16.6	19.3
Internal	4.6	5.1	5.9	6.9	8.0
Subtotal	23.8	26.6	30.8	36.0	41.7
Fallout					
External gamma	1.1[a]	0.18	0.21	0.25	0.29
Inhalation	0.27[a]	0.008	0.009	0.11	0.013
Ingestion	1.0[a]	0.63	0.83	1.0	1.3
Subtotal	2.4[a]	0.82	1.1	1.3	1.6
Other					
Reactors	0.000016	0.00043	0.0061	0.023	0.056
Fuel reprocessing	-	0.00017	0.0050	0.025	0.065
Worldwide ^{3}H	0.0031	0.0092	0.0071	0.0067	0.0084
Worldwide ^{85}Kr	0.00002	0.00008	0.0007	0.004	0.012
PNE tests	0.00003[b]	-	-	-	-
Nevada Test Site	0.0088[c]	-	-	-	-
Other AEC installations	0.0026	0.0025	0.0027	0.0033	0.0038
Subtotal	0.015	0.012	0.022	0.062	0.15
TOTAL	24.8	27.4	31.9	37.4	43.4
Population (millions)	183	205	237	277	321
Man-rem/10^6 people	136,000	134,000	135,000	135,000	135,000

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[a] 1963 value. A 1960 total fallout value of 1.0 was used in the TOTAL of all environmental radiation.

[b] 1962 dose; not used in totals. PNE is peaceful nuclear explosives.

[c] Sept. 15, 1961 to Sept. 15, 1962 dose. This value was used in the 1960 totals.

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APPENDICES
TO
ENVIRONMENTAL RADIATION SECTION

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APPENDIX II-A

Accumulated Bone Dose from ^{90}Sr vs. Age
(Determination of Figure II-2)

The bone dose values in Figure II-2 were calculated using different ^{90}Sr diet data and values of dose per μCi intake for different age groups. The intake of ^{90}Sr varies for different age groups depending primarily on the quantity of milk consumed in the diet. Adult diets[38] are used for people over 20 years old, teenage diets[36] for ages 2 to 20, and infant diets (half the adult intake)[37] for up to 2 years old. These age groupings were selected to correspond to the available data.

The United States average ^{90}Sr intake used for each of the three age groups is given in Table IIA-1. Adult diet data[38] were available for 1960 to 1970 for three cities and teenage diet data[37] were available for 1963 to 1969 for 10 cities. Chicago was in both groups and provided a means of comparison between teenage and adult diets. For 1954 to 1959 the ratio ^{90}Sr/Ca in milk was available for adults.[104] For years when no data were available, various ratios given at the end of the table were used to convert from one age group to another. The average was determined for 1963, 1965, and 1969 for 12 regions of the United States, each represented by one of the cities for which diet data were available. A national average was then determined using the populations of the 12 regions and the data from the 12 cities. The 1970 fraction of the population in each age group[105] was used for all years. The national average was approximately a factor of 1.2 times the average of New York City and San Francisco. This factor was used for other years.

Each yearly dietary intake was considered taken at midyear for calculational purposes. For the year of birth, an intake of half that for adults (to account for fetal dose) plus half that for infants was assumed. Changes in this assumption would not change the accumulated dose significantly.

Values of dose imparted to bone per unit of activity intake used in the calculations were:

Infant[106]: 1st year dose; 1.24 rem/μCi intake 1st year
2nd year dose: 1.52 rem/μCi intake 1st year + 2.02 rem/μCi intake 2nd year

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Table 11A-1

Strontium-90 Intake
(pCi/yr.)

Year	Infant (ages 0 to 2)	Teen (ages 2 to 20)	Adult (>age 20)
Pre-1954	0	0	0
1954	193	580	386
1955	560	1,680	1,120
1956	900	2,700	1,800
1957	900	2,700	1,800
1958	1,520	4,560	3,040
1959	2,200	6,600	4,400
1960	1,675	5,020	3,351
1961	1,434	4,300	2,869
1962	1,993	5,980	3,986
1963	4,698	17,700	9,395
1964	4,687	16,400	9,373
1965	3,690	10,840	7,380
1966	2,617	7,960	5,234
1967	2,420	6,263	4,840
1968	2,037	5,970	4,073
1969	1,818	4,818	3,635
1970	1,785	4,640	3,570
Post-1970	1,785	4,640	3,570

Notes:

Adult data: 1954-1959 ratio ^{90}Sr/Ca in milk[104] (pCi/g Ca) x 400 = pCi/yr. ("400" varies from 330 to 480 for 1960-1968).

1960-1970[37] U.S. Average = $\frac{\text{New York + San Francisco}}{2} \times 1.2$.

Infant data: 0.5 of adult data.[37]

Teen data: 1963-1969 (from Reference 37)
1954-1962, 1.5 times adult data for same years
1970 and after, 1.3 times adult values (less because of less deposition resulting in less influence of milk on total intake).

Teen and adult[37,105]: 50-year dose (after age 2)
= 9.1 rem/μCi intake during
1st two years
+ 8.4 rem/μCi intake after age 2.

The fraction of the 9.1 rem or 8.4 rem accumulated each year after intake is given in Table IIA-2. Several of these values had been calculated based on a decline of ^{90}Sr in the body according to the equation $t^{-n}e^{-\lambda t}$ where t is time after intake in days, n is 0.20 for ^{90}Sr, and λ is the ^{90}Sr decay constant.[107] These values were plotted, a curve drawn, and then the values of fractional accumulated dose for each year after intake were taken from the curve.

The accumulated dose at various ages was determined by summing the dietary intakes times the accumulated dose per unit activity intake for the number of years after intake being considered. These dose values are presented in Figure II-2.

Table IIA-2

Fraction of 50-year ^{90}Sr Bone Dose Delivered after Intake[107]

Years after Intake	Fraction of Dose Delivered	Years after Intake	Fraction of Dose Delivered
1	0.072	26	0.741
2	0.121	27	0.757
3	0.169	28	0.770
4	0.210	29	0.783
5	0.246	30	0.798
6	0.274	31	0.810
7	0.313	32	0.821
8	0.344	33	0.834
9	0.373	34	0.846
10	0.402	35	0.857
11	0.428	36	0.867
12	0.456	37	0.878
13	0.484	38	0.888
14	0.510	39	0.898
15	0.534	40	0.909
16	0.555	41	0.919
17	0.577	42	0.929
18	0.600	43	0.937
19	0.619	44	0.946
20	0.636	45	0.956
21	0.655	46	0.965
22	0.675	47	0.975
23	0.693	48	0.985
24	0.708	49	0.993
25	0.726	50	1.000

APPENDIX II-B

Dose Calculational Methods for Fuel Reprocessing

1. Whole-body Gamma Doses

Whole-body gamma dose rate from a single radionuclide, due to immersion in a cloud of radioactivity can be determined from the equation:

$$D_i = \frac{2\pi}{10^3} \cdot \frac{\Gamma_i C_i}{\mu_i} \text{ rem/hr.}$$

where μ is the linear attenuation coefficient for air, C is the average air radionuclide concentration in μCi/cm^3, and Γ is the gamma exposure rate constant in (R-cm^2)/(hr.-mCi) for the radionuclide being considered. The above equation is obtained by taking half of an integration over an infinite sphere of radioactivity. Assuming μ is constant over the range of gamma energies of interest, each radionuclide can be related to ^{137}Cs by the following ratio:

$$\frac{D(\text{nuclide } i)}{D(^{137}\text{Cs})} = \frac{\Gamma_i C_i}{\Gamma_{Cs} C_{Cs}}$$

The ^{137}Cs dose rate was taken from a detailed calculation for the Hanford, Washington, area[58] and multiplied by six since the dilution factor for Hanford is six times lower than the dilution factor used in this study.

2. Skin Doses and Doses Due to Inhalation

^{3}H Whole-body dose rate = $3.6 \cdot 10^4 X \cdot 1.4$ rems/week where X is the air concentration[44] in μCi/cm^3 and the factor 1.4 takes into account an increase in dose due to organic labelling from chronic exposure.[70] Skin dose rate = $1.7 \cdot 10^3 X$ rems/week.[44] (All organ doses are in addition to whole-body doses.)

^{85}Kr Skin dose rate (0.07 mm depth) = $\frac{300X}{3 \cdot 10^{-7}}$ mrem/yr.[59,61]

Lung dose rate = $\frac{5X}{3 \cdot 10^{-7}}$ mrem/yr.[61]

^{133}Xe Skin dose rate (surface) = $0.23\bar{E}X\Delta t$ (Reference 58) where $\bar{E}$ = 0.112 Mev (the average beta energy of ^{133}Xe) and $\Delta t = 3.15 \cdot 10^7$ sec./yr.

^{133}Xe Skin dose (0.07 mm depth) = 0.20 • surface dose.[58]

Lung dose rate = $\frac{2.3X}{3 \cdot 10^{-7}}$ mrem/yr.

from a comparison with ^{85}Kr lung doses.

^{144}Ce Bone dose rate = $\frac{3 \cdot 10^{4}X}{3 \cdot 10^{-9}}$ mrem/yr.[34]

Lung dose rate = $\frac{1.5 \cdot 10^{4}X}{2 \cdot 10^{-9}}$ mrem/yr.[34]

^{129}I Thyroid dose rate = $\frac{3 \cdot 10^{4}X}{6 \cdot 10^{-10}}$ mrem/yr.[34]

^{131}I Thyroid dose rate = $\frac{3 \cdot 10^{4}X}{3 \cdot 10^{-9}}$ mrem/yr.[34]

^{90}Sr Bone dose rate = X • 20 • 10^{6} cm^{3}/day air intake • 365 days/yr. • 0.7 • 10^{3} mrem/50 yr./μCi intake.[35]

Pu Isotopes and Other Actinides

For ^{239}Pu:

bone dose rate = 226 • 10^{3} mrem/50 yr./μCi intake,

lung dose rate = 588 • 10^{3} mrem/50 yr./μCi intake, and

respiratory lymph node dose rate = 132 • 10^{6} (mrem/50 yr.)/μCi intake.[36]

Plutonium-238 and ^{240}Pu were considered equivalent to ^{239}Pu because their MPC_a's are the same.[34] Other nuclides (^{241}Pu, ^{241}Am, ^{242}Cm, ^{244}Cm) were compared to ^{239}Pu by using ratios of their MPC_a's for different body organs.[34] Whole-body MPC_a ratios were used for bone and respiratory lymph node doses and lung MPC_a ratios were used for lung doses.

Other Nuclides

Lung dose rate = $\frac{15 \cdot 10^{3}X}{10^{-8}}$ mrem/yr.

since the MPC_a of most radionuclides is greater than 10^{-8} μCi/cm^{3}. Those with lower MPC_a's were individually checked to determine their significance.

3. Doses Due to Ingestion of Surface Deposition

Dose values from Dresden calculation:[57]

Nuclide	Critical Organ	Release Rate (pCi/sec.)	Dose at 3,000 m (mrem/yr.)
^{89}Sr	Bone	7,300	$5.4 \cdot 10^{-3}$
^{90}Sr	Bone	5	$8.2 \cdot 10^{-5}$
^{131}I	Thyroid	550	$3.4 \cdot 10^{-1}$
^{137}Cs	Whole-body	123	$1.8 \cdot 10^{-4}$

$$^{129}\text{I thyroid dose} = 5 \cdot \frac{\text{R.R. } (^{129}\text{I})}{\text{R.R. } (^{131}\text{I})} \cdot {}^{131}\text{I dose} \cdot 10$$

where R.R. is the release rate of the ^{129}I or ^{131}I, the 5 takes into account the difference in thyroid dose for the same concentrations,[34] and the factor 10 (a gross estimate) takes into account the buildup of ^{129}I in the environment because of its long half-life.[44]

III. MEDICAL RADIATION

In this section, doses to the United States population resulting from radiation exposures in the healing arts are discussed under the following headings: Medical and Dental Radiology, Diagnostic Use of Radiopharmaceuticals, Radiation Therapy, and Medical Occupational Exposure.

A. Dose Estimates

At present, the use of radiation in the healing arts is recognized as the largest manmade component of radiation dose to the United States population. This includes medical diagnostic radiology, clinical nuclear medicine, radiation therapy, and occupational exposure of medical and paramedical personnel. Drawing comparisons between radiation doses to the population from medical x-rays and other sources of exposure is difficult. First, the radiation is delivered to an individual largely on the basis of the professional judgement of an individual practitioner. Second, a limited portion of the body is normally exposed during X-ray examinations as contrasted with the whole-body exposure received from many other sources, and this exposure is intermittent and delivered at high dose rates, as opposed to the constant low-level exposure from most other sources. This dissertation is presented to estimate doses accrued to specific exposed populations and to the United States population as a whole from the medical uses of radiation; in addition, trends in the use of radiation in the healing arts and their effect on radiation dose will be explored. Extrapolations and projections made in this study concerning specific organ doses and future population doses are, in all cases, based on presently available data and assume a continuity of parameters cited in the original base line information.

1. Medical and Dental Radiology

The potential mutagenic effect of x radiation received from medical exposure led early to a dosimetric designation that would adequately express genetic significance. Genetically significant dose (GSD) is one index of radiation received by the genetic pool. This index permits comparisons between diverse national surveys and serves as an important

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measure of x-ray exposure. Estimates of the components of this index have permitted the identification of those medical x-ray procedures which contribute most to the genetic effect of radiation and thus focuses corrective action on them. Mathematically, the GSD is expressed as:

$$\mathrm{GSD} = \frac{\Sigma D_i \hat{N}_i P_i}{\Sigma N_i P_i}$$

where D_i = the average gonad dose to persons age i who receive x-ray examinations,

$\hat{N}_i$ = the number of persons in the population of age i who receive x-ray examinations,

P_i = the expected future number of children for a person age i,* and

N_i = the number of persons in the population of age i.

The magnitude of x-ray dose to segments of the United States population has been reported in numerous studies (Appendix III-A).[1-10] These studies have been limited to estimations of GSD or, in some cases, to gonad dose. Population studies of x-ray dose resulting from diagnostic radiology vary as to time of inception (beginning in 1953), scope (local or national), population size and characteristics, survey methods, and dosimetry. One of the objectives of this review is to estimate some doses of somatic significance from available published and unpublished information.

a. Methodology and Results of United States Studies; Genetically Significant Dose

Calculation of GSD for a population group is subject to broad variations. National and local population studies most often obtain the annual GSD by weighting the individual gonad doses received during x-ray examinations by the number of individuals examined and by the relative

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*Assumes an equal fertility rate in the x-rayed population being studied and the total population.

contribution of these persons to the expected number of future children produced by the population. An alternative procedure is to estimate the mean annual gonad dose to that segment of the population below the age of 30 and consider it equivalent to the GSD. The equivalence of the two methods is based on the preponderance of potential child-bearing and child-fathering individuals in the age group below 30.

Changes in diagnostic radiographic techniques and their relative rate of use (influenced by the year the study was conducted and the location where it was performed) have a great effect upon the results obtained. In addition, parameters such as the health characteristics and the fraction of the population exposed, the accuracy of gonadal dose determination, and the method by which x-ray machine output is measured; all these influence the estimates made from a survey and limits comparisons between surveys.

Estimates of United States population GSD range from 18 to 136 mrem according to different reports.[1-10] This variation is influenced by relative child expectancy, age and sex distribution of the subjects, usage distribution of specific examinations, and gonad dose per examination. While no one variable can account for the differences in the results obtained, the incidence of obstetrical examinations and the weight given to doses from these examinations appear to explain, to some extent, some of the differences in the range of values reported. For example, examinations of pregnant women provided approximately 30% of the total GSD in New Orleans (1962),[3] while the contribution of pregnant women in the Public Health Service 1964 study was very small.

Published information from the Public Health Service survey of x-ray exposure in the United States indicates a GSD of 54.6 mrem in 1964.[1] Preliminary information from a repeat study in 1970 yields a GSD of 35.5 mrem.[11] At this time, the significance of this difference cannot be clearly evaluated because information as to the magnitude of the uncertainty surrounding these results has not as yet been published. Although the error in the representativeness of the entire population sample is small,[12] the representativeness of dose estimates in any specific examination-age-sex group can significantly influence the result. For example, in 1964 lumbo-sacral and lumbar-spine examinations of 15- to

29-year old males accounted for 30% of the entire GSD (16.5 mrem).[1] Furthermore, approximately 70%* of the difference between the 1964 and 1970 results are attributable to this examination-age-sex group.[11]

Testicular exposure of individuals in this examination-age-sex group is relatively infrequent, but because of the magnitude of the potential testicular dose from this examination and the child expectancy of this age group, these doses have a large influence on the resultant population GSD. The magnitude of the testicular dose appears to depend on whether or not the testes are in the direct x-ray beam. Accordingly, when the testicular doses from the PHS 1964 survey are plotted, they tend to follow a bimodal distribution,[13] the lower dose peak corresponding to examinations in which the testes are out of the direct beam and the upper dose peak corresponding to examinations in which the testes are in the direct beam. The degree of certainty surrounding the determination of testicular dose in this examination-age-sex group is dependent upon the number of measurements made. The data indicate that the number of measurements in the 1964 and 1970 surveys of this examination-age-sex group were limited.[13] The small number of examinations in which testicular doses were measured and the nature of the distribution introduce uncertainty into the available GSD information.

b. Extrapolation of Other Doses

(1) Abdominal Dose

In order to evaluate somatic implications of the radiation doses received by the population from diagnostic x-ray usage, dose estimates for specific organs are needed. Such estimates are generally not yet available for the U.S. As a first step in estimating an approximate relative somatic dose, one might determine the mean dose in the center of the abdomen. (It must be remembered that the true specific organ doses depend on many parameters such as field size, type of projection, etc.) An index of the abdominal dose is provided by the PHS studies of 1964 - 1970, which produced ovarian dose estimates for each procedure completely reported in the surveys, regardless of patient sex. This information has not been previously published. The ovarian and "simulated ovarian doses" were computed as the mean of the estimated left and right ovarian doses generated for each examination for which dose could be calculated in the PHS study files.[14] The per capita ovarian* and "simulated ovarian doses" weighted for representation in the United States population will, for the sake of simplicity and to differentiate them from the true gonad doses** be referred to as the "abdominal dose." Because the entire population regardless of age was employed, the data were not weighted for future child-bearing potential, and the dose estimates were not as sensitive to small variations in beam size and position, the difficulties encountered in determination of GSD were reduced. The "abdominal dose" values are presented as an index of somatic dose in an effort to provide an alternate to the GSD estimates and to establish a basis for analyzing contributing factors and evaluating future trends. The biological significance of the "abdominal dose" is not evaluated in this report, nor have these estimates been used to develop values for other organs. The unequal distribution of body areas exposed, the non-homogeneity of human tissue, and variations of dose with age, all preclude such application.

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*[16.5 mrem (1964 GSD contribution from male lumbo-sacral lumbar-spine 15-29-year age group) minus at least 3.2 mrem (maximum estimate 1970 GSD contribution from male lumbo-sacral lumbar-spine 15-29-year age group)] ÷ [54.6 (1964 GSD) minus 35.5 (1970 GSD)].

The estimated abdominal doses for 1964 and 1970 (based on preliminary data) are presented in table III-1. Results are not presently available for fluoroscopy during 1970, and these doses have been estimated from the ratio of radiography to fluoroscopy doses in 1964. An estimate of the abdominal dose from dental examinations was not made, but this would be less than 0.3 mrem annual per capita dose since no dental film in the Public Health Service survey produced an estimated gonad dose higher than 0.2 mrem.[1] Considering only the exposed population (i.e., only persons receiving x-ray examinations), the abdominal dose for males remained the same in 1970 as it had been in 1964 while that for females appears to have risen. The reason for the rise in female dose needs to be elucidated. The annual per capita abdominal dose to the whole United States population appears to have increased by about 20%, the entire increase being due to the rise in the female dose.

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*Estimates made using the dose model yield ovarian and "simulated ovarian doses" at a depth of 10 cm.

**The true gonad doses being the ovarian dose for females and testicular dose for males.

Table III-1

Estimated Abdominal Dose from Diagnostic Radiology

(Simulated Ovarian Dose - Male; Ovarian - Female)

Year	Annual per Capita Dose for the Exposed Population (mrem)			Size of Exposed Population (thousands)	Fraction of Whole U.S. Population	Annual per Capita Dose for the Whole U.S. Population (mrem)
	Male	Female	Both			
1964						
Radiography	150	126	138	66,086	0.354	49
Fluoroscopy	273	318	296	7,779	0.042	12
Total						61
1970*						
Radiography	148	156	153	75,400	0.377	58
Fluoroscopy**	269	394	328	8,600	0.043	14
Total						72

*Preliminary results.
**Estimate based on ratio Radiography/Fluoroscopy for 1964.

(2) Thyroid Dose

Because of their proximity to the thyroid gland, examinations of the head and neck, chest, and mouth are most likely to contribute to the thyroid dose. Estimates of thyroid dose (Appendix III-B) indicate that for the exposed population in 1964, the per capita thyroid dose was 172 mrem from examinations of the head and neck. For the population as a whole the annual per capita dose was about 7 mrem. This large difference is due to the relatively small size of the population experiencing this type of examination in 1 year. If one were to assume that the ratios of doses to the lens of the eye and to the thyroid gland for head and neck examinations and for dental examinations are the same, the estimates above may be made. Such a procedure does not take into account differences in X-ray beam projections and in beam geometry. With the same reservations, assuming that the ratio of the skin dose to the male gonad dose for abdominal examinations has the same ratio as the skin dose to the thyroid dose for chest examinations, one is able to estimate thyroid doses of 171 mrem from a photofluorographic chest examination and 15 mrem from a radiographic chest examination. Thus, in 1964, the per capita thyroid dose for the exposed population from chest examinations was 69 mrem while the corresponding dose for the whole population was 19 mrem. No estimates have been made of the contributions of examinations of the abdomen and extremeties to thyroid dose due to virtually a complete lack of information.

During 1964, 226,700,000 dental films were taken.[12] According to the distribution of film types used[15] and estimates of thyroid dose per film for each film type,[16,17] the per capita thyroid dose in 1964 was 57 and 14 mrem in the exposed and whole populations, respectively. A summary of annual per capita thyroid doses from medical and dental diagnostic radiography is presented in Table III-2.

Table III-2

Estimated Thyroid Doses from Diagnostic Radiology

Source	Annual per Capita Dose for the Exposed Population (mrem)	Size of Exposed Population (thousands)	Fraction of Whole U.S. Population	Annual per Capita Dose for the Whole U.S. Population (mrem)
Examinations of head and neck (1964)	172	7,500	0.04	7
Examinations of chest and thorax (1964)	69	51,100	0.27	19
Dental examinations (1964)	57	45,900	0.25	14

2. Diagnostic Use of Radiopharmaceuticals

Other sources of radiation doses in the healing arts, more recent in terms of use than x-ray machines, are radiopharmaceuticals. These materials find use in the diagnosis, and in a few specific cases in the treatment of disease. Because of their newness, exposed populations are still limited in size. However, there is strong evidence of the increased use of these radiation sources.

a. Genetically Significant Dose

An early estimate (1956) of genetically significant dose from the medical uses of radionuclides indicated a dose of 8 mrem per person per year.[18] This analysis was based on the total quantity of ^{131}I and ^{32}P shipped during the year, including both diagnostic and therapeutic uses, and did not include age selection and procreative potential. A subsequent analysis (1957),[19] assuming a diagnostic examination rate of 150,000 to 200,000 per year, of which probably not more than 25,000 examinations were performed per year on patients below age 30, indicated that the total accumulated patient gonad dose accrued from the diagnostic use of ^{131}I would be 375 rem (sum of doses to all exposed individuals) to this younger age group. The genetically significant dose would be equivalent to 0.004 mrem, assuming that 50% of the noninstitutional civilian population was below age 30. An equal genetically significant dose was alleged to be accrued through other diagnostic radionuclide procedures for a total annual GSD of 0.008 mrem.

More recent information (1966)[20] on radiopharmaceutical usage patterns provided a basis for evaluating an estimated total accumulated gonad dose of 195,000 rem (sum of doses to all exposed individuals) from all diagnostic radiopharmaceutical procedures to all age groups. Again, if one assumes that 12.5% of the individuals receiving these procedures are below age 30, and that 50% of the total population is also below age 30, then the 1966 estimated annual GSD is 0.26 mrem from the diagnostic use of radiopharmaceuticals.

b. Extrapolations of Other Doses

Calculation of radiation doses to specific organs from radiopharmaceuticals requires a knowledge of three parameters: (a) radiopharmaceutical usage rates, (b) activity per patient administration, and (c) the dose delivered to a specific organ per unit activity administered. During a 1966 Public Health Service study,[20] questions were asked of 7,204 physicians licensed to use radionuclides in medical practice. The reported number of patient administrations of various pharmaceuticals in specific procedures was based on the response of 54% of those queried. In some cases, this study also documented the average activity administered per procedure for a 70 kg-male. For those procedures where these latter data were missing, the recommended activity administered per procedure was obtained from a current text[21] and/or the manufacturer's literature. The organ specific doses per unit activity administered represent the median values from a range of values recently published.[22] However, the authors acknowledge that reliable biological data necessary for absorbed-dose calculations is unavailable for many nuclear medicine procedures. Thus, only limited information on all of the required parameters is available. Based on this information, the cumulative radiation dose to a specific organ from a specific radionuclide was calculated (Appendix III-C). The estimated annual per capita doses for the exposed population and for the whole United States population from the diagnostic use of radiopharmaceuticals in 1966 are presented in Table III-3.

The most significant dose was that accrued to the thyroid from administration of ^{131}I. Most of this dose was due to the performance of ^{131}I thyroid function tests and scans. If the recommended dose* had been administered, the estimated thyroid dose per procedure would have been 5 to 15 rem (depending on dose administered and thyroid size) for a function test and 50 to 150 rem for a thyroid scan.[21] Based on meager reports on actual practice in 1966, the average activity of ^{131}I administered per thyroid function test was reported to be 27 μCi and the average activity administered per thyroid scan was 46 μCi.[20] Unfortunately, the data on the average activity administered are from a very limited number of responses (30). In the case of thyroid function tests, the data on the average activity administered from the Public Health Service survey exceeded the quantities recommended in current practice.[21] Using the reported data,

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*5-10μCi for uptake and 50-100μCi for scan.

Table III-3

Estimated Doses from the Diagnostic Uses of Radiopharmaceuticals - 1966

Specific Organ Dose	Annual per Capita Dose for the Exposed Population (mrem)	Size of Exposed Population (thousands)	Fraction of Whole U.S. Population	Annual per Capita Dose for the Whole U.S. Population (mrem)
Thyroid				
^{131}I thyroid function	5 to 15 x 10^3	481	0.0025	37*
(^{131}I thyroid function	47 x 10^3	481	0.0025	117)**
^{131}I thyroid scanning	78 x 10^3	252	0.0013	101
^{131}I other	1.6 x 10^3	320	0.0017	2.7
^{99m}Tc brain scans	2.4 x 10^3	104	0.0005	1.2
^{125}I thyroid scans	67 x 10^3	2	10^{-5}	0.7
Other radionuclides	-	339	0.0018	-
TOTAL				143* (220)**
Gonads				
^{131}I thyroid function	69	481	0.0025	0.17
^{131}I thyroid scanning	114	252	0.0013	0.15
^{131}I other	86	320	0.0017	0.15
^{203}Hg	630	89	0.0004	0.25
Other radionuclides	134	356	0.0019	0.25
TOTAL				1.0
Whole body				
^{131}I thyroid function	55	481	0.0025	0.14
^{131}I thyroid scanning	91	252	0.0013	0.12
^{131}I other	44	320	0.0017	0.07
Other radionuclides	279	445	0.0023	0.64
TOTAL				1.0

*Based on recommended activity per administration.

**Based on small survey sample.

the estimated annual per capita thyroid dose to the whole population was 220 mrem. If the recommended dose for thyroid function tests was administered, the annual per capita whole population thyroid dose would have been 143 mrem. Despite the relatively small size of the exposed population, administration of radiopharmaceuticals for thyroid tests contributes the major radiation dose to the thyroid gland. It is interesting to note that the dose from an ^{125}I thyroid scan is only moderately lower than that of an ^{131}I scan. The dosimetric advantages of ^{125}I over ^{131}I are partially negated because more is administered per procedure. The radiopharmaceutical ^{99m}Tc, available from ^{99m}Tc-^{99}Mo generators, has been found a useful substitute for ^{131}I in certain scanning procedures. The thyroid dose from this nuclide is low relative to ^{131}I.

Other than ^{131}I, radiopharmaceuticals which deliver relatively high doses to an individual experiencing a diagnostic procedure are ^{203}Hg and ^{198}Au. The annual per capita dose to the whole body when considered for the population as a whole, is approximately 1 mrem.

3. Radiation Therapy

The treatment of cancer with radiation is an established medical modality, the object of which is the delivery of large quantities of radiation to the diseased tissue. With this purpose in mind, and because radiation exposure is not considered an undesirable side effect in therapy procedures as it is in diagnostic radiography, it appears judicious to estimate population dose from radiation used in treating cancer only in terms of the genetically significant dose for the whole United States population. In the use of radiation in nonmalignant diseases, where other modalities of treatment may be available and the use of radiation may be more open to question, population dose could be calculated both in terms of GSD and specific organ doses. Unfortunately, information relative to the use of radiation for the treatment of nonmalignant disease is sparse.

a. Radiation Treatment of Cancer

In order to obtain an estimate of the population GSD from radiotherapy of cancer, several informational items are required:

(1) the number of individuals less than 30 years of age having a particular malignant disease first diagnosed in any one year,

(2) the proportion of the above individuals receiving radiation therapy,

(3) the proportion of individuals receiving radiation therapy and surviving,

(4) the gonad dose per treatment, and

(5) the reduction in fertility due to the disease itself*

Information on and estimates of these parameters, albeit in different time periods, are presented in Appendix III-D. Using the incidence of cancer in Connecticut in 1966,[23] the occurrence, by age distribution and by type and site of the malignancy, can be approximated for the entire United States. Unpublished data were made available[24] that provided information on the proportion of persons treated with radiation and the 5-year survival rates in the under-30 age group for the years 1955 through 1964. It is estimated that malignant diseases occurred in 93,000 individuals under the age of 30 in the United States during 1966, and that approximately 25,000 were treated with radiation (X-ray, teletherapy, and brachytherapy not differentiated).

Having established occurrence, treatment, and survival rates, estimates of gonad dose and appropriate fertility rates are required. No comprehensive United States information on this subject appears to exist and British data for 1957[25] seem to provide the best approximation of United States practice. In some cases, the data used for gonad doses are maximum estimates, since for treatment of cancers of unspecified sites (lymphomas, leukemia, endocrine tissue, and melanomas), doses found during treatment of the lower abdomen, pelvis, and upper thigh were employed. In these cases, a correspondingly lower fertility rate was also used in the calculations.

Assuming that the gonad dose to the population under age 30 is a measure of the population GSD and that the size of this population is

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*For example, females receiving radiation therapy to the pelvic region were assumed to have no future childbearing potential. For the reduced fertility factors employed see Appendix III-D, Table III-D-5.

50% of the total noninstitutional civilian population, then the estimated annual GSD from radiation therapy of malignant disease is approximately 5 mrem.

No estimate of the GSD from use of radiopharmaceuticals and radium in the treatment of malignant diseases is made since there is little likelihood that the number of persons under age 30 treated in such a manner would be large.[19]

b. Radiation Treatment of Nonmalignant Diseases

Radiation therapy has been used for the treatment of nonmalignant conditions of the skin such as acne and eczema, inflammatory processes such as bursitis and spondylitis, and other conditions. There is no significant information concerning the usage and doses accrued to the United States population from this application of radiation.

Unpublished information from the 1964 study (which was not published because its relative standard sampling error was 25%) indicated that approximately 597,000 persons received 3,445,000 radiation therapy procedures in 1964, of which 1,700,000 procedures were directed to the skin of the head.[1] It is estimated that 525,000 procedures (relative standard error of approximately 50%) were to the skin of the head to the age group below 30 years. Based on the age of the population involved and the fact that approximately 70% of these procedures were administered by dermatologists, it is likely that the majority of these procedures were for nonmalignant skin conditions. These same data indicate that the approximate average number of exposures per patient is four. Given the large sampling error, one might estimate that the population at risk under age 30 experiencing radiation therapy to the head was 131,500.

If a commonly suggested technique is employed (75 R per treatment to each side of the face, 50 to 100 kVp), then the estimated gonad dose is 1.5 mrem.[26,27] The annual per capita GSD from dermatological therapy to the head is thus relatively low and is estimated to be 0.008 mrem. Information on doses to other organs, specifically for the lens of the eye and thyroid gland, is not available. Although the contribution of these types of examinations to the gonad dose and GSD is minimal, it should be mentioned that somatic doses to a sizable group of individuals may be high.

For the most part, administration of radiopharmaceuticals for therapy of nonmalignant illnesses in the under-30 age group is limited to the treatment of hyperthyroidism.[19] This procedure accounted for 61.4 percent of radiopharmaceutical therapy procedures for all ages in 1966.[20]

The estimates of the extent of use of radiation in the United States for treatment of nonmalignant conditions are based on tenuous data. Unfortunately, suitable data are not available. Neither is information available on specific organ doses. From studies in other countries prior to 1962, it was reported that GSD's were as high as 4.5 rem from the use of radiation in nonmalignant diseases.[28]

4. Medical Occupational Exposure

Estimation of dose accrued to the population because of occupational associations with the delivery of medical radiation is constrained, in that only film badge data are available and various agencies and facilities define an occupationally exposed individual differently. Unpublished data on occupational radiation exposure from medical sources present information gathered in several States.[29] Film badge data serve as the only available index of whole-body dose.

An independent analysis of this information, presented in detail elsewhere in this report, indicates the following mean annual doses: medical x-ray workers 320 mrem, dental x-ray workers 125 mrem, radioisotope workers 262 mrem, and radium workers 540 mrem.

A population at risk of 195,000 and 171,000 persons in 1968 has been reported for the medical and dental occupational exposure groups, respectively.[30] Counting radium and radioisotope workers, the total exposed population is estimated to be approximately 454,000 persons so that the annual per capita dose to the United States population as a whole is 0.56 mrem (see IV below).

B. Projected Doses

1. Medical and Dental Radiology

Projections of doses from diagnostic medical radiography must take into consideration a variety of variables. These include changes in the rate of delivery of radiographic examinations, in the age and sex distribution of the patients, in the distribution of examinations by type, and in the dose per examination. In the case of GSD, the projected fertility rate per age group also may influence the resultant estimate. Furthermore, future doses will be influenced by technical, educational, and regulatory actions which could modify patient dose. These variables are difficult to evaluate, and projections of radiation dose from medical radiation must be evaluated with consideration for the uncertainties involved.

Film sales provided an early estimate of increased usage of radiological services. Between 1945 and 1965, film sales increased at the rate of 5.4% per annum.[31] More recent preliminary evidence indicates that film usage has increased at the rate of 4.7% per annum.[32] Information relative to changes in patient usage rates is probably more pertinent to changes in radiation dose than are increases in film sales or use. A study in selected hospitals indicates that between 1963 and 1968 the annual rate of discharges of patients in any diagnostic radiation category and in total diagnostic radiation categories increased by 3.6 and 6.6%, respectively.[33] Preliminary information from the 1970 Public Health Service study yields a somewhat lower indicator of the rate of delivery of radiographic medical examinations. Based on the 1964 and 1970 studies, the examination rate for medical diagnostic radiography increased from 61.8 examinations per 100 persons in 1964 to 68.5 examinations per 100 persons in 1970 or a 1.6% increase per annum.[32] Thus, the information presented above leads to an estimate of between 1 and 4% increase per annum in the rate of delivery of radiographic procedures. At least some of this increase appears to be due to the expansion of radiology services to persons who previously did not have such care available (i.e., persons with low family income and in the age group over 65).[32]

Other available information relevant to projected dose pertains to potential reduction in patient dose due to improved collimation and technique. Experience in a large teaching hospital showed that about 30% of radiation dose delivered pursuant to x-ray examinations could be reduced by optimization of technique.[6] This is inclusive of 10% unnecessary radiation due to repetitive examinations. In particular, optimization of technique could reduce the amount of radiation dose delivered in a gastrointestinal tract examination by 20% and in other abdominal examinations by 27%.[6] The effect of collimation in dose reduction is dependent upon the procedure, position, and film size. Reductions in bone marrow dose due to collimation appear to vary from 17 to 80%; while for gonad dose, exclusion of the gonadal regions from the direct beam can reduce the dose by a factor[34] of 5. Gonadal shielding is particularly important in reduction of male gonad doses, and, reportedly, reduces this dose by about 92% for a shield acceptable to most patients.[35] An optimistic evaluation of the reduction of genetically significant dose by collimation indicates that a large reduction is possible through simple restriction of beam size to film size.[1] In practice, this is not accomplished easily or carried out routinely, since it requires care in positioning the patient and x-ray tube, as well as selection of proper cone or x-ray field size adjustment. From the above discussion it appears reasonable that as much as a 50% reduction in dose might be possible due to technical and educational methods.

In fact, there is some evidence that technical improvements are occurring. While a survey of x-ray facilities between 1963 and 1968 indicated that at least 28% of medical x-ray machines were improperly collimated.[15] A comparison of the 1964 and 1970 Public Health Service studies shows that collimation improved in all types of x-ray facilities during this period.[32]

The information presented in this report comparing the estimates of GSD and annual per capita abdominal dose for 1964 and 1970 is such that no firm conclusions can be drawn at this time as to changes. In view of the possible decrease in the GSD and increase in the abdominal dose estimates shown by the Public Health Service 1964 and 1970 studies, and the fact that the magnitude of the uncertainty surrounding these figures has not, as yet, been determined, no firm conclusion can be drawn at this time as to future radiation doses. If one assumes that there is no change with time in the mean abdominal dose to the whole population, i.e., if technical improvements keep pace with increased usage, then the man-rem received by the population depends only upon population size.

Using an annual per capita abdominal dose of 72 mrem would yield the projected man-rem listed in Table III-4.

Table III-4

Estimated Total Man-rem to the United States Population from Medical Diagnostic Radiology - 1960 to 2000

Year	Population (millions)	Estimated Total Man-rem (millions)
1960	183	13.2
1970	205	14.8
1980	237	17.1
1990	277	19.9
2000	321	23.1

Dental x-ray visit rates during 1961 and 1964 are similar, with a slight decrease during the latter year being attributable to sampling differences.[1,36] Between 1964 and 1970,[32] a gradual rise of about 4% per year in the rate of dental x-ray visits is evident. Using a per capita dental x-ray visit rate of 0.27 and an average of five films per visit, the predicted whole-body man-rem to the United States population from dental x-rays in the year 2000 is less than 200,000.

2. Radiation Therapy

The purposeful delivery of radiation in the case of radiation therapy is an argument against the inclusion of this source of radiation in estimates of accumulated man-rem doses to the population. There is no significant information to indicate the direction that the doses from radiation therapy will take in the future even though its use might increase.

3. Diagnostic Radiopharmaceuticals

Studies of radiopharmaceuticals indicate increases in the rate of administrations of between 15 and 20% per year in the mid-1960's.[31,37] More recent information based on sales of radiopharmaceuticals indicates an annual increase of 25% per year.[38] It appears judicious to estimate that in the 1960's the use of radiopharmaceuticals increased fivefold during the 10-year period and that an increase of sevenfold may be experienced in the next 10 years. Thereafter, it is difficult to make predictions, especially in terms of dose since technical changes are likely to play a large role in dose reduction in a rapidly changing field. Assuming no technical changes, and the growth pattern indicated above, it is expected that the whole-body man-rem to the United States population in 1980 from diagnostic use of radiopharmaceuticals will be 3.3 million man-rem. Even with a slowing of the rate of increased use of radiopharmaceuticals the accrued whole-body man-rem could easily reach approximately 15% of the total dose from medical uses by the year 2000.

Improvements in equipment have led to decreased dosage requirements in thyroid function tests and kidney scans, and the substitution of radionuclides yielding lower patient exposure have already reduced total body and kidney doses per procedure. Even with these improvements, in the 4-year period, 1964 to 1968, one institution reports that the average whole-body dose per patient increased from 100 mrem to 160 mrem due to the increased use of radiopharmaceuticals.[37]

4. Medical Occupational Exposure

Projections of future occupational dose are based on the growth expectation for medical and dental personnel. This projection assumes that the manpower requirements for the radiological sciences are growing at the composite compounded rate of 7.1% per year.[31] For dental personnel projected doses are based on approximately 0.87 dental workers per 1,000 population and it is assumed that this ratio (which has remained fairly constant) will continue.[39] Using the dose estimates previously presented, the projected accrued annual whole-body man-rem dose to the United States population by the year 2000 is less than 0.2 million man-rem.

C. Summary

A summary of estimated doses from medical and dental radiation is presented in Table III-5.

The genetically significant dose provides one index of the magnitude of radiation dose to the population from the use of radiation in the healing arts. The main contributor to the GSD in 1964, reported to be 55 mrem,[1] was diagnostic medical radiography. The genetically significant

Table III-5

Summary of Estimated Doses from Medical and Dental Radiation

Dose Category or Organ	Source	Annual per Capita Dose for Exposed Population (mrem)	Size of Exposed Population (thousands)	Fraction of Whole U.S. Population[a]	Annual per Capita Dose for Whole U.S. Population (mrem)
Genetically significant dose[b]					
(1964)	Medical and dental diagnostic radiography				55
(1970)	Same				36[c]
(1966)	Radiation therapy				5
(1966)	Radiopharmaceuticals				0.3
"Abdominal dose"[d]					
(1964)	Medical radiography				
	Radiography	138	66,900	0.40	61
	Flouroscopy	296	7,780		
(1970)	Radiography	153	75,400	0.42	72[c]
	Flouroscopy	328	8,600		
Whole-body dose (1966)	Diagnostic uses of radiopharm.	Depends on radiopharm.	1,500	0.008	1

(continued)

Table III-5 (continued)

Dose Category or Organ	Source	Annual per Capita Dose for Exposed Population (mrem)	Size of Exposed Population (thousands)	Fraction of Whole U.S. Population[a]	Annual per Capita Dose for Whole U.S. Population (mrem)
Whole-body dose occupational (1968)	Medical workers	320	454	0.002	0.6
	Dental workers	125			
	Radiopharm. and radium workers	262-540			
Organ					
Thyroid (1964)	Medical radiography				
	Examinations of head and neck	172	7,500	0.31	26
	Examinations of chest and thorax	69	51,100		
	Dental radiography	57	45,900	0.25	14
Thyroid (1966)	Diagnostic uses of radiopharm.				
	^{131}I thyroid function function	5 to 15×10^3[e]	1,500	0.008	143
	^{131}I thyroid scan	78×10^3			
	Other	Depends on radiopharm.			

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[a] Based on civilian non-institutionalized population only.
[b] GSD applicable to whole United States population.
[c] Preliminary information.
[d] Ovarian and "simulated ovarian" doses.
[e] Based on recommended activity per administration.

doses from dentistry and radiopharmaceuticals were small; less than 1 mrem for dentistry (1964) and 0.3 mrem for radiopharmaceuticals (1966). The GSD (1966) from radiotherapy was estimated to be 5 mrem. Preliminary reports have stated that the GSD has decreased from the 1964 level to 35.5 mrem in 1970.[11] A large portion (30%) of the GSD in 1964 was due to lumbo-sacral and lumbar-spine examinations of males in the 15- to 29-year age group. This examination-age-sex group also accounts for approximately 70% of the difference in the GSD between 1964 and 1970. The small number of examinations in this category for which testicular doses were actually measured, and the nature of the distribution of the data, has introduced reservations concerning the conclusiveness of the results.

Another index of medical radiation dose used in this report is the per capita abdominal dose. This index is calculated from dose estimates, ovarian (for females) and "simulated ovarian" (for males), weighted for their representation in the United States population. Because the entire population regardless of age is employed, the data are not weighted for future child-bearing potential, and the dose estimates are not sensitive to small variations in beam size and position; the difficulties encountered in determination of GSD are reduced. Furthermore, one is able to calculate dose estimates for the exposed population (i.e., considering only persons receiving x-ray examinations). The annual per capita abdominal depth dose for the exposed population in 1964 was 138 and 296 mrem from medical radiography and fluoroscopy, respectively. In 1970, based on preliminary information, the abdominal dose due to medical radiography appears to have risen. This increase, due entirely to an elevation of the female per capita abdominal dose, requires elucidation. For the whole United States population, the annual per capita abdominal doses for 1964 and 1970 are estimated to have been 61 and 72 mrem, respectively. Errors in the survey and the measurements from which these estimates were derived have not, as yet, been fully evaluated. Accordingly, it appears that the most prudent conclusion is that this index has remained relatively stable during the two study years.

Estimates of whole-body dose may also serve as an index of somatic dose. Whole-body doses from radiopharmaceuticals may be relatively high (approximately 1 rem) to individuals experiencing a particular procedure; however, because the number of persons so treated is still relatively small, the accrued dose to the whole population is small.

Among specific organs which may be exposed in the course of medical treatment, present information permits estimates of thyroid dose. The highest thyroid doses are delivered to individuals experiencing ^{131}I thyroid function and scan tests who receive an estimated per capita dose of 5 to 15 rem to this organ during a thyroid function test and 78 rem during a thyroid scan. The introduction of in vitro thyroid function tests and new radiopharmaceuticals will significantly lower these doses. Although the population receiving such procedures is small, the annual per capita thyroid dose to the whole United States population (1966) from radiopharmaceuticals is estimated at 143 mrem. This is greater than the corresponding estimated annual per capita doses to the whole population (1964) of 26 mrem from medical x-ray examinations of the head, neck, chest, and thorax and 14 mrem from dental radiography.

A word should be said about occupational doses associated with the delivery of medical x-rays and therapy. Estimated annual per capita doses (1968) to exposed groups of workers range from 125 mrem for occupational dental exposure to 540 mrem for persons employed in administration of radium therapy. As a group, medical workers contribute a greater portion to overall population dose than any other occupational group, and experience a higher annual per capita dose than any other occupational group.

Among pertinent information required for a more complete evaluation of radiation doses to the United States population from the healing arts, but as yet, still lacking are bone marrow doses from the medical radiation sources. Also, doses from the treatment of nonmalignant diseases with radiation, and doses to particular populations at maximum risk due to specific chronic illnesses are also not available.

Projection of doses from diagnostic medical radiography must take into consideration changes in the rate of delivery of radiographic examinations, in the age and sex distribution of the patients, in the distribution of examinations by type, and in dose per examination. Review of several reports on the rate of increase of radiographic examinations, each using different measurement parameters, leads to the conclusion that in the past decade the rate of radiological examinations increased between 1 and 4% per year. At least some of this increase appears to be due to the expansion of radiographic services to persons who previously did not have such care available. Furthermore, there is some evidence of technical improvements, and it is reasonable that as much as a 50% reduction in dose might be possible due to technical and educational methods. Thus, it appears that the potential for technical improvement could keep pace with increased usage. Based on the evaluations presented in this report of the Public Health Service surveys of 1964 and 1970, it appears that the reported changes in the GSD are, at present, uncertain and require further elucidation. An evaluation of abdominal dose, based on these same surveys, leads to the conclusion that the level of population dose between 1964 and 1970 from diagnostic medical radiology has not changed greatly. Considering the above factors, the man-rem dose from diagnostic medical radiation would increase only through population increase. An annual per capita abdominal depth dose (an index of somatic dose) of 72 mrem in 1970 would yield an estimated 14.8 million man-rem to the whole United States population. Increasing population alone would raise this to 23.1 million man-rem by the year 2000.

Compared to diagnostic medical radiography, estimated future accrued man-rem doses to the United States population from other medical uses of radiation are small. Only the diagnostic uses of radiopharmaceuticals, which by the year 2000 could accrue a whole-body man-rem dose of greater than 3.3 million man-rem to the population, is significant. The corresponding accrued man-rem doses from dentistry and medical occupational exposure in the year 2000 are 200,000 man-rem each.

Extrapolations and projections made in this study must be considered in light of the uncertainties surrounding the base measurement, the assumptions employed, and the changing state of medical technology. Despite these reservations, medical radiation is the largest manmade component of radiation dose to the United States population. It accounts at present, on the basis of the indices employed in this study for at least 90% of the total manmade radiation dose and at least 35% of the total radiation dose (including natural background) to which the United States population is exposed. Conclusive evidence that doses from diagnostic medical radiography has either increased or decreased in the past decade is lacking. Based on the information presently available and discussed in this report, it is logical to conclude that the annual per capita population dose from diagnostic medical radiography could remain stable if technical improvements keep pace with increased usage rates.

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APPENDICES
TO
MEDICAL RADIATION SECTION

APPENDIX III-A

Summary of Information Relating to United States Studies for Determination of GSD

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Table IIIA-1

Summary of Information Relating to United States Studies for Determination of GSD

Study and Location	Year	Approx. No. Persons x rayed or Exams.	Site or Sampling Source	See Footnotes	Source of Population Age Distribution Data	Source of Age-Specific Child Expectancy Data
Public Health Service/National[1]	1964	4,500	Household interview	a,b,c	Study itself	National Center for Health Statistics, 1963
Izenstark & Lafferty/ New Orleans, La.[3]	1962-1963	8,000 persons	Hospitals & offices	c	Study itself	National Center for Health Statistics, 1963
Pasternak & Heller/ New York, N.Y.[4]	1962	Not reported	Gen., TB & mental hosp., clins., offs.	a,c	NYC Census-1960	Not reported
Cooley & Beentjes/ Galveston, Tex.[5]	1964	220,000 examinations	University hospital	a,b,c	U.S. Census-1960	U.S. Vital Statistics - 1960
Morgan & Gehret/ Baltimore, Md.[6]	1963-1964	36,000 persons	Teaching hospital	a,c	U.S. Census-1960	National Center for Health Statistics, 1963
Billings, Norman, & Greenfield/ Los Angeles, Calif.[7]	Prior to 1957	900 persons	Large private & general hosp., childrens clin.	d	Study itself	-
Laughlin & Pullman[8]	1957	-	Based on published literature	a,b,d	-	American Medical Directory, 1950, 1956

(continued)

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Table IIIA-1 - continued

Study and Location	Year	Approx. No. Persons x rayed or Exams.	Site or Sampling Source	See Footnotes	Source of Population Age Distribution Data	Source of Age-Specific Child Expectancy Data
Brown, Heslep, & Eads/ San Francisco, Calif.[9]	1956-1957	110,000 examinations	Medical ins. hospital	a,d	Study itself	-
Norwood, Healy, Donaldson, Roesch, & Kirklin/ Richland, Wash.[10]	1953-1956	85,000 examinations	Hospital & offices	a,b,c,d	Study itself	Study itself

[a] Flouroscopy included.

[b] Dentistry included.

[c] GSD based on age distribution and child expectancy.

[d] GSD equivalent to 30-yr. gonad dose.

Table IIIA-2

Summary of Information Relating to United States Studies for Determination of GSD

Study and Location	Dose Model Employed	Actual Measurement of X-ray Machines Made During Study		Method of Measurement of X-ray Machines During Study	GSD[a] (mrem)
		Yes	No		
Public Health Service/National[1]	Phantom & human subjects	X	-	Various film packs depending on procedure	55
Izenstark & Lafferty/New Orleans, La.[3]	Phantom	-	X	-	(New Orleans) 75
Pasternak & Heller/New York, N.Y.[4]	Model based on phantom	-	X	-	(New York City) 50
Cooley & Beentjes/Galveston, Tex.[5]	Phantom, human subjects & published lit.	X	-	Assortment of ionization chambers and/or monitoring films	18
Morgan & Gehret/Baltimore, Md.[6]	Calculational (relationship between abdominal & gonad dose)	X	-	Differential-type ionization chambers	23
Billings, Norman, & Greenfield/Los Angeles, Calif.[7]	Phantom & human subjects	-	X	-	(L.A. hospital) 61
Laughlin & Pullman[8]	Based on published literature	-	X	-	(probable) 136 (minimum) 50
Brown, Heslep, & Eads/San Francisco, Calif.[9]	Based on published literature	-	X	-	40
Norwood, Healy, Donaldson, Roesch, & Kirklin/Richland, Wash.[10]	Phantom & published literature	Partial	-	Ionization chambers	(Richland) 46

[a] For U.S. population unless otherwise stated. Not differentiated between estimates to population less than 30 and whole population.

APPENDIX III-B

Estimated Thyroid Dose - 1964

A. Head and Neck Examinations

1. 27,069,000 films[12] or 7,519,166 examinations assuming 3.6 films per examination.

2. Mean skin exposure (skull, mastoid, optic, mandible, and sinuses) = 279 mR per examination.[12]

3. Assume that the skin dose and dose to the lens of the eye are equivalent.

4. Ratio of lens of eye to thyroid exposure:

   14 periapical films[16]

   @ 65 kVp 2.1:1.3 = 1.61
   @ 90 kVp 79:48 = 1.64.

5. $$\frac{\text{279 mR lens of eye /examination}}{1.62} = \text{172 mrad thyroid dose/examination}^{*}$$

6. $$\frac{\text{7,519,000 examinations x 172 mrad/examination}}{187 \times 10^{6} \text{ whole population}} = \frac{1.293 \times 10^{9}}{187 \times 10^{6}} = \text{6.9 mrad annual per capita thyroid dose.}$$

B. Chest Examinations

1. Assume ratio of skin to thyroid dose from chest examinations same ratio as skin to male gonad doses from abdominal examinations.

   $$\frac{\text{Abdominal mean male gonad dose/film}^{1}}{\text{Abdominal mean skin dose/film}^{12}} = \frac{\text{273 mrad}}{\text{790 mrad}} = 0.34\ \frac{\text{abdominal gonad}}{\text{abdominal skin}}.$$

2. Mean skin dose - chest x rays:

   Chest (photofluorographic)/film[12] = 500 mrad.
   Estimated thyroid dose = 170 mrad.

   Chest (radiographic)/film[12] = 45 mrad.
   Estimated thyroid dose = 15 mrad.

3. Dose 1963:

   No. chest films (photofluorographic)[12] (1964) = 16,800,000 x 170 mrad
   = 2,900,000 rad.

---

*Assumes mR and mrad to be equivalent.

No. chest films (radiographic)[12] (1964) = 46,800,000 x 15 mrad
= 702,000 rad

Total = 3,600,000 rad.

$$\frac{3{,}567{,}730 \text{ patient-rad (1964)}}{51{,}100{,}000 \text{ persons at risk}} = 0.069 \text{ rad} = 69 \text{ mrem to person in exposed population.}$$

$$\frac{51{,}100{,}000 \text{ exposed population} \times 69 \text{ mrem}}{187 \times 10^{6} \text{ total population}} = 0.27 \times 69 = 19 \text{ mrem mean annual per capita dose to whole population.}$$

C. Dental Examinations

1. 226.7×10^{6} films/yr.[17]

2. Distribution by film use[15] (percent).

Film type	Bite wing	Periapical
A	3	3
B	48	47
C	17	18
D	32	32

3. Distribution of film use by type of film[17] (percent).

Periapical	67
Bite wing	33

4. Thyroid dose per film (mrem).

Bite wing		Periapical	
Film Speed	Dose	Film Speed	Dose
A	44	A	27.2
B	22[17]	B	13.6
C	11	C	6.8
D	5.5	D	3.4[17]

5. Dose (1964):

Bite wing

$$D = \frac{226.7 \times 10^{6} \times 0.33 \quad (0.03 \times 44) + (0.48 \times 22) + (0.17 \times 11) + (0.32 \times 5.5)}{45.9 \times 10^{6}}$$

= 25.279 mrem mean annual dose to person in population at risk.

Periapical

$$D = \frac{226.7 \times 10^6 \times 0.67 \quad (0.03 \times 27.2) + (0.47 \times 13.6) + (0.18 \times 6.8) + (0.32 \times 3.4)}{45.9 \times 10^6}$$

= 31.502 mrem mean annual dose to person in population at risk.

$$\frac{45.9 \times 10^6 \text{ exposed persons}}{187 \times 106 \text{ total population}} \times 56.78 \text{ mrem} = 13.93 \text{ mrem per capita to population as a whole.}$$

APPENDIX III-C

Radiopharmaceuticals

Table IIIC-1

Patient Administration and Dose Administered - 1966

Radionuclide and Form	Procedure	Estimated number of patient administrations[a] (1966)	Dose administered[b] (μCi/70-kg adult)
^{131}I			
NaI	Thyroid uptake	481,830	27.5
NaI	Thyroid scanning	252,567	45.7
Labelled albumin	Blood volume	163,418	5.5
Labelled albumin	Cardiac output	2,527	20
Labelled albumin	Placental scanning	6,753	7.1
Labelled albumin	Brain scanning	6,077	400
Labelled albumin	Heart scanning	675	300
Labelled albumin	Liver scanning	337	157.7
Labelled albumin(MAA)	Lung scanning	37,817	260.4
Sodium Iodohippurate	Renal function	53,069	45.0
Sodium Iodohippurate	Kidney scanning	3,376	200
Labelled fats	Fat malabsorption	12,635	44.4
Rose Bengal	Hepatic function	1,685	10
Rose Bengal	Liver scanning	32,415	150
^{125}I			
NaI	Thyroid scanning	2,026	75
Other radionuclides			
^{57}Co Labelled Vitamin B_{12}	Vitamin B_{12} absorption	39,591	0.50
^{60}Co Labelled Vitamin B_{12}	Vitamin B_{12} absorption	26,113	0.50
^{51}Cr Sodium chromate	Blood volume	36,221	27.3
^{51}Cr Sodium chromate	Red blood cell survival	10,108	100
^{51}Cr Heat-treated red blood cells	Spleen scanning	2,701	225
^{59}Fe chloride or citrate	Iron turnover	5,054	7.5

(continued)

Table IIIC-1 - continued

Radionuclide and Form	Procedure	Estimated number of patient administrations[a] (1966)	Dose administered[b] (μCi/70-kg adult)
^{99m}Tc pertectnetate	Brain scanning	103,998	7,936.6
^{99m}Tc pertectnetate	Thyroid scanning	337	2,000
^{99m}Tc sulfur colloid	Liver scanning	4,911	2,971.6
^{99m}Tc labelled albumin	Placental scanning	205	1,000
^{99m}Tc labelled albumin	Lung scanning	205	1,000
^{198}Au colloidal gold	Liver scanning	68,881	175.0
^{203}Hg labelled mercurials	Brain scanning	62,128	700
^{203}Hg labelled mercurials	Kidney scanning	27,012	116.6
^{197}Hg labelled mercurials	Brain scanning	30,389	1,000
^{197}Hg labelled mercurials	Kidney scanning	11,480	144.4
Mercurihydroxipropane	Spleen scanning	675	300
^{85}Sr nitrate or chloride	Bone scanning	675	2,000
^{75}Se selenomethiodine	Pancreas scanning	2,701	125

[a] Represent returns[20] from 54% of queried, corrected to estimate total patient administrations.

[b] Values stated to one decimal place from Reference 20. Mean dose is average representative of all physicians performing procedure. Assumes a 70-kg adult patient, except for ^{131}I, where weighted average was used. Other values represent median dose recommended[21,22] or values from manufacturer's literature.

Table III-C-2

Dose per Administration

Radionuclide and form	Procedure	Dose (mrad)*		
		Whole body	Gonad	Thyroid
^{131}I				
NaI	Thyroid uptake	55	69	46,750
NaI	Thyroid scanning	91	114	77,690
Labelled albumin	Blood volume	11	30	193
Labelled albumin	Cardiac output	40	110	800
Labelled albumin	Placental scanning	14	39	248
Labelled albumin	Brain scanning	800	2,200	14,000
Labelled albumin	Heart scanning	600	1,650	10,500
Labelled albumin	Liver scanning	315	867	5,519
Labelled albumin	Lung scanning	65	208	9,110
Sodium iodohippurate	Renal function	5	25	1,575
Sodium iodohippurate	Kidney function	24	-	7,000
Labelled fats	Fat malabsorption	29	-	-
Rose Bengal	Hepatic function	7	-	-
Rose Bengal	Liver scanning	105	-	-
^{125}I				
NaI	Thyroid scanning	3	-	67,500
Other Radionuclides				
^{57}Co labelled Vitamin B_{12}	Vitamin B_{12} absorption	1.75	50	-
^{60}Co labelled Vitamin B_{12}	Vitamin B_{12} absorption	210	280	-
^{51}Cr sodium chromate	Blood volume	5.5	6.8	-

(continued)

Table IIIC-2 - continued

Radionuclide and form	Procedure	Dose (mrad)		
		Whole body	Gonad	Thyroid
^{51}Cr sodium chromate	Red blood cell survival	20	25	-
^{51}Cr heat-treated red blood cells	Spleen scanning	67	450	-
^{59}Fe chloride or citrate	Iron turnover	225	1,125	-
^{99m}Tc pertectnetate	Brain scanning	119	198	2,831
^{99m}Tc pertectnetate	Thyroid scanning	30	198	600
^{99m}Tc sulfur colloid	Liver scanning	44	297	-
^{99m}Tc labelled albumin	Placental scanning	15	40	-
^{99m}Tc labelled albumin	Lung scanning	15	40	-
^{198}Au colloidal gold	Liver scanning	218	87	-
^{203}Hg labelled mercurials	Brain scanning	1,050	630	-
^{203}Hg labelled mercurials	Kidney scanning	175	630	-
^{197}Hg labelled mercurials	Brain scanning	100	80	-
^{197}Hg labelled mercurials	Kidney scanning	14	11	-
Mercurihydroxipropane	Spleen scanning	42	36	-
^{85}Sr nitrate or chloride	Bone scanning	1,312	-	-
^{87m}Sr nitrate or chloride	Bone scanning	20	-	-
^{75}Se Selenomethiodine	Pancreas scanning	1,000	625	750

*Product of activity per administration and dose[22] to specific organ per unit activity.

APPENDIX III-D

Radiation Therapy

Table III D-1

Exposed Population Radiation Therapy (Malignancies) Age <30

ICS No.	Rate/100,000 in Conn.[23] 1966 Male	Rate/100,000 in Conn.[23] 1966 Female	Site	Expected number of cases in U.S.* Male	Expected number of cases in U.S.* Female
140 - 149	1	-	Buccal cavity & pharynx	553.8	-
151	-	1	Stomach	-	538.3
153	1	3	Large intestine	553.8	1,615.0
154	1	1	Rectum	553.8	538.3
155	-	1	Liver, bile duct	-	538.3
157	-	1	Other, digestive	-	
160	1	-	Nose and nasal cavity	553.8	-
162	1	-	Lung bronchio-tracheal	553.8	-
163	2	1	Other, respiratory	1,107.6	538.3
170	-	1	Breast	-	538.3
171	-	110	Uterus (excluded from genetic dose)		
172	-	3			
174	-	3			
175	-	7			
177	2	-	Prostate		
178	11	-	Other male genitals		
180	2	2	Kidney	1,107.2	1,077.2
181	1	-	Bladder	553.8	-
181.7	1	-	Other urogenital	553.8	-
190	9	9	Malignant melanoma	4,984.2	4,845.0
192	2	1	Eye	1,107.6	538.6
193	9	13	Brain	4,984.6	6,997.9
193.1	4	4	Other central nervous system	2,215.2	2,153.3
194	5	8	Thyroid	2,769.0	4,306.6
195	1	1	Other endocrine	553.8	538.3
197	8	7	Connective tissue (bone)	4,430.4	3,768.3
199	2	3	Other	1,107.6	1,615.0
Lymphatic	19	17	Lymph	10,522.2	9,151.1
Leukemia	18	12	Leukemia	9,968.4	6,460.0

*Estimated Population to Age 30 (1970): Male; 55,385,000
Female; 53,833,000.

Table III-D-2

Treatment of Cancer (Diagnosed 1955-1964) with Radiation[a] - Age <30

Site	All Cases		Treated with Radiation		Relative Survival Rate[b] (%)			
					All Cases		Radiation Treated	
	Number	Percent	Number	Percentage of Cases	3 yr.	5 yr.	3 yr.	5 yr.
Lip	22	0.2	3	14	95	95	-	-
Tongue	17	0.2	8	47	-	-	-	-
Salivary gland	379	3.4	19	5	97	94	(79)	(79)
Floor of mouth	3	0.1	3	100	-	-	-	-
Mouth (other)	23	0.2	6	26	-	-	-	-
Oral mesopharynx	10	0.1	9	90	-	-	-	-
Nasopharynx	62	0.6	53	85	(37)	(31)	(35)	(35)
Hypopharynx	2	0.1	2	100	-	-	-	-
Pharynx, NOS	3	0.1	2	67	-	-	-	-
Esophagus	1	0.1	1	100	-	-	-	-
Stomach	40	0.4	9	22	(16)	-	-	-
Small intestine	36	0.3	14	39	(32)	(32)	-	-
Large intestine	305	2.8	7	2	76	71	-	-
Rectum	51	0.5	3	6	(48)	(42)	-	-
Liver/gallbladder	73	0.7	14	19	15	13	-	-
Pancreas	32	0.3	6	19	(21)	(21)	-	-
Peritoneum	8	0.1	5	62	-	-	-	-
Digestive, NOS	1	0.1	1	100	-	-	-	-
Nose, nasal cavity, ear, etc.	50	0.5	[illegible]	66	(53)	(45)	(50)	-

(continued)

Table III D-2 (continued)

Site	All Cases		Treated with Radiation		Relative Survival Rate[b] (%)			
					All Cases		Radiation Treated	
	Number	Percent	Number	Percentage of Cases	3 yr.	5 yr.	3 yr.	5 yr.
Larynx	15	0.1	8	53	(91)	-	-	-
Bronchus, lung	89	0.8	30	34	(41)	(36)	(18)	(11)
Mediastinum	89	0.8	62	70	(33)	(31)	(37)	(33)
Breast	195	1.8	81	42	53	44	(38)	(29)
Cervix, uteri	351	3.2	215	61	72	67	57	53
Corpus, uteri	37	0.3	9	24	(86)	(86)	-	-
Ovary, fallopian tubes, etc.	186	1.7	85	46	68	64	(59)	(52)
Vulva, vagina	19	0.2	5	26	-	-	-	-
Prostate	12	0.1	8	67	-	-	-	-
Testis	327	3.0	175	54	52	51	52	50
Penis, other male genitals	12	0.1	0	-	-	-	-	-
Kidney	278	2.5	216	78	41	40	38	38
Bladder	88	0.8	9	10	84	84	-	-
Other, urinary	7	0.1	0	-	-	-	-	-
Lower GI, NOS	0	-	0	-	-	-	-	-
Melanoma	369	3.3	9	2	70	64	-	-
Other skin	264	2.4	24	9	95	92	(82)	(82)
Eye	381	3.5	125	33	86	84	82	81
Brain, other nervous system	1,600	14.5	811	51	38	33	34	28

(continued)

Table III-D-2 (continued)

Site	All Cases		Treated with Radiation		Relative Survival Rate[b] (%)			
					All Cases		Radiation Treated	
	Number	Percent	Number	Percentage of Cases	3 yr.	5 yr.	3 yr.	5 yr.
Thyroid	613	5.6	143	23	97	96	94	92
Other endocrine glands	233	2.1	143	61	34	32	34	32
Bone	485	4.4	252	52	32	28	24	19
Connective tissue	444	4.0	137	31	52	50	27	26
Ill-defined sites	169	1.5	37	51	13	13	14	14
Lympho/reticulo sarcoma	413	3.7	260	63	24	18	26	20
Hodgkins disease	904	8.2	678	75	52	31	55	34
Other lymphoma	100	0.9	34	34	40	37	(43)	(43)
Multiple myeloma	5	0.1	2	40	-	-	-	-
Leukemia	2,167	19.6	165	8	4	3	3	3
Mycosis fungoides	5	0.1	1	20	-	-	-	-
ALL SITES COMBINED	11,034	100	3,976	36				

[a] Radiation alone or in combination with other therapy.

[b] Rates in parentheses have standard error between 5 and 10%. Rates with standard errors larger than 10% not shown.

Table III D-3

Estimated Gonad Dose per Treatment[25]

Site	Dose (rem) Male	Dose (rem) Female
Buccal cavity and pharnyx	0.22	0.25
Stomach	9.07	16.94
Large intestine	212.09	-
Rectum	385.2	-
Liver and bile duct	5.38	10.04
Nose and nasal cavity	0.51	0.57
Breast	-	7.79
Lung, bronchi and trachea	2.05	5.94
Other respiratory	2.05	5.94
Kidney	44.74	-
Bladder	262.59	71.71
Melanoma*	88.37	150.0
Eye	0.2	0.22
Brain	0.4	0.44
Other central nervous system	0.4	0.44
Thyroid	0.45	1.0
Other endocrine	44.74	405.0
Connective tissue*	141.39	240.0
Lymphoma*	123.72	210.0
Leukemia*	123.72	210.0

*Depends on site-assumed, treatment situated on lower abdomen, pelvis or upper thigh.

Table III-D-4

Gonad Dose from Radiation Therapy of Malignancies to the Less Than 30 Age Group

Site	Product of Percentage of Population <30 Treated by Radiation & 10-year Survival Rate	Estimated Population <30 Having Malignancy, Receiving Radiation, & Surviving >5 Years		Gonad (patient-rem per year)	
		Male	Female	Male	Female
Buccal cavity and pharynx	0.10 (0.145 x .70)	55	-	12.1	-
Stomach	0.04 (.22 x .16)	-	21	-	355.7
Large intestine	0.01 (.02 x .70)	5	16	1,060.4	3,393.6
Rectum	0.03 (.06 x .50)	17	16	6,548.4	6,163.2
Liver, bile duct	0.03 (.19 x .14)	-	16	-	160.6
Nose and nasal cavity	0.33 (.66 x .50)	183	-	93.3	-
Breast	0.12 (.42 x .29)	-	66	-	514.1
Lung, bronchi and trachea	0.04 (.34 x .11)	22	-	45.1	-
Other respiratory	0.48 (.53 x .91)	532	258	1,090.6	1,532.5
Kidney	0.30 (.78 x .38)	332	323	14,840.4	14,438.1
Bladder	0.08 (.10 x .84)	44	-	11,554.4	-
Other urogenital		-	-	-	-
Melanoma	0.01 (.02 x .64)	50	48	4,420.0	7,200.0
Eye	0.26 (.33 x .81)	288	140	57.6	30.8
Brain	0.14 (.51 x .28)	698	980	279.2	431.2
Other central nervous system	0.14 (.51 x .28)	310	301	124.0	132.4

(continued)

Table III D-4 (continued)

Site	Product of Percentage of Population <30 Treated by Radiation & 10-year Survival Rate	Estimated Population <30 Having Malignancy, Receiving Radiation, & Surviving >5 Years		Gonad (patient-rem per year)	
		Male	Female	Male	Female
Thyroid	0.21 (.23 x .92)	581	904	261.4	904.0
Other endocrine	0.19 (.61 x .32)	105	102	4,693.5	41,310.0
Connective tissue	0.08 (.31 x .26)	353	301	49,914.2	72,240.0
Lymphoma	0.25 (.34 x .75)	2,631	2,288	325,454.7	480,480.0
Leukemia	0.02 (.08 x .03)	199	129	24,616.3	27,090.0
Other	0.14	155	226	13,697.3	33,900.0
TOTAL		6,560	7,814	448,363.9	690,276.2

Table III D-5

Estimated GSD from Radiation Therapy (Malignant Diseases)

Area of Body	Fertility Index Relative to Normal[25]	Annual Cumulative Patient-rem		Annual Cumulative Patient-rem Corrected for Fertility
		Male	Female	
Male genitals	0.02	-	-	-
Male pelvic region	0.40	490,670	-	196,268
Male - other	1.0	1,936	-	1,936
Female pelvis (bladder, cervix, rectum, and kidney)	0.0	-	-	-
Female pelvic region	0.4	-	681,184	272,473
Female - other	1.0	-	3,545	3,545

Note: $\frac{474{,}249 \text{ patient-rem}}{93.5 \times 10^6 \text{ population under 30}} = 5.1 \text{ mrem.}$

IV. OCCUPATIONAL RADIATION

The contribution of occupational exposure to the population dose from ionizing radiation is poorly documented in the scientific literature. Despite the lack of published information, a vast quantity of data has been accumulated in various personnel dosimetry programs throughout the United States. Most of the information from these programs has been made available for this study. The purpose of this section is to provide mean dose estimates for various occupational specialities, an estimate of the total number of radiation workers in the population, and an estimate of the contribution of occupational exposures to the United States population dose.

A. Assumptions and Limitations of Data

In general, the data collected by the various reporting agencies were primarily for verification of the adequacy of radiation protection practice and to preclude, where possible, overexposure of the worker. The retention of the data by the employer is, in most instances, for medicolegal purposes. There is no requirement for uniformity in collecting or reporting of all occupational exposures to ionizing radiation nor are there any required standards for accuracy.

In consideration of the foregoing, the data collated by major reporting agencies will be treated separately. In numerous instances, the major reporting agency includes data from other agencies through joint agreements to provide personnel dosimetry service. Where possible, these will be shown.

Except where indicated, the doses are from external sources. Information on dose from internal sources during occupational exposure is limited and is reported only for special categories. The terminology used by the reporting agencies is extremely varied. It has been assumed that the value reported is the exposure of the dosimetry device and no

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attempt has been made to calculate a true absorbed dose. Additional complications in assessing a true dose are variations in placement of the dosimeter on the individual and variations in the terminology used in reporting results; i.e., reports made in roentgens, rad, and rem. For the purposes of this report, the value reported is considered to be accurate; to be a whole-body dose and is assumed to be the dose equivalent in rem. It is intended that the use of dosimeter exposure results as dose equivalent will result in an overestimate of the actual whole-body dose[1].

With the exception of data obtained from the Army and Navy, all results were provided in dose ranges. For the purpose of calculating total man-rem, the midpoint of the ranges were taken to be the mean for the entire range. Since there is a tendency to badge for convenience, and for legal purposes, it has been reported that in most cases those individuals who have no detectable exposure are included in the lowest dose range. The arbitrary assignment of unexposed workers to the lower end of the distribution skews the data and would underestimate the overall mean dose of those exposed. To compensate for this bias, the midpoint has been established as the mean.

In addition to the assumption that all reported exposures are accurate, it has been assumed that all overexposures were true individual doses. In only a limited number of cases was there any indication that an investigation had been conducted following an overexposure or that any adjustment in the individual's dose had been made.

B. Summary of Data from Reporting Agencies

Below are discussed the data reported by Federal agencies and other organizations.

1. Federal Agencies

The reporting Federal Agencies include: the Army, Air Force, Navy, Atomic Energy Commission, and Public Health Service.

a. Army

The Army employs approximately 22,790 individuals who may be exposed to ionizing radiation as a result of their duties. Sources to which Army personnel may be exposed are quite varied. Radiation protection practice and control of sources is established by regulation and strictly enforced. All exposure records are maintained at two processing centers (Sacramento and Lexington Bluegrass Army Depots) which provided individual annual doses for this study[2]. For purposes of this evaluation, individuals exposed as a result of employment to greater than 10 mrem/yr. have been considered to be radiation workers. It has been suggested[3] that individuals receiving an annual dose of less than 10 mrem should be considered as "occasionally exposed individuals."[3]

The method of reporting exposure data was such that the broad categories of occupational specialities could be identified as medical, industrial, and reactor fields.

As shown in Table IV-1 the average dose per worker (>10 mrem/yr.) in the medical field is 95 mrem, industrial field 94 mrem, and the reactor field, 245 mrem.

Table IV-1

Summary of Army Annual Occupational Doses - 1969 to 1970

Job Category	Percent of Workers	Percent in Dose Range (rem)				Mean (mrem)
		0-0.1	0.1-0.5	0.5-1.5	>1.5	
All	100	96	3.2	0.68	0.02	100
Medical	49.6	-	-	-	-	95
Industrial	46.5	-	-	-	-	94
Reactor	3.8	-	-	-	-	245

Included in the data provided by the film badge processing facilities is dose information from other Government agencies, such as the National Bureau of Standards and from some National Aeronautics and Space Administration facilities.

b. Air Force

The Air Force monitors 34,975 individuals who may be exposed to ionizing radiation in the course of their work. The Radiological Health Laboratory at Wright-Patterson AFB provides dosimetry service and serves as a repository for exposure data for the Air Force. All doses for this study were provided by that agency through the Surgeon General, Department of the Air Force[4].

The system developed by the Air Force not only records individual doses but categorizes them in terms of dose groups for a specific occupational specialty.[5,6] Table IV-2 shows the mean annual dose for selected occupational areas. Through discussions with personnel at the Radiological Health Laboratory, it was determined that anyone having a recorded dose less than 10 mrem/yr. was included in the 10 to 49 mrem range. An estimate of the number of these individuals was deducted from total monitored personnel prior to determining the mean dose in each job category. The calculated mean annual dose for Air Force occupational exposure is 88 mrem.

Table IV-2

Summary of Air Force Occupational Doses - 1969 to 1970

Job Category	Percent of Workers	Mean Annual Dose (mrem)
Medical X-ray	23	101
Dental X-ray	19	77
Veterinary X-ray	1	67
Medical nuclide	3	100
Industrial nuclide	19	68
Industrial X-ray	12	79
Radar	8	67
Special weapons	4	89
Reactors	1	461
Miscellaneous	10	98
TOTAL	100	88

Percent of Workers

Dose Range (rem/yr.)

0-0.049	.049-.099	.1-.299	.3-.499	.5-1.49	1.5-2.99	3-4.99	>5
95.7	2.4	0.9	0.6	0.3	0.05	0.02	0.02

c. Navy

Occupational exposure data for the Navy are maintained by the Naval Medical Data Services Center, Bethesda, Maryland. Exposure data on 55,051 individuals was provided for this study through the Radiation Safety Office, National Naval Medical Center[7] (see Table IV-3).

Table IV-3

Summary of Navy Occupational Doses - 1969 to 1970

Job Category	Percent of Workers	Mean Annual Dose (mrem)
Medical	10	83
Industrial	90	211
TOTAL	100	198

d. Atomic Energy Commission

The Atomic Energy Commission maintains dosimetry records for employees and contractors who routinely work with byproduct material and special nuclear material. The 1969 data used for this study included exposures to 102,918 employees. The format was in dose ranges of 1 rem from 0 to 12 rem.[8,9]

To determine the total man-rem, the low range of 0 to 1 rem was divided into smaller increments corresponding to those reported for Atomic Energy Commission and agreement State licensees. The percentage of employees assigned to each range was assumed to be comparable to licensees. The reported ranges and the estimated ranges are shown in Table IV-4. The total man-rem was calculated to be 20,361. This results in an overall mean annual dose of 198 mrem per worker.

e. Public Health Service

The Public Health Service provides dosimetry for all its activities, as well as for the Bureau of Prisons and the Coast Guard. The sources of exposure in these agencies are similar to those found in the practice of medicine and dentistry throughout the United States.

A thorough analysis of the results of this dosimetry program was furnished for this study.[10] During fiscal year 1970, film badge records were maintained for 2,750 individuals. Of this number, 508 exceed 10 mrem. For this group the mean annual dose was 129 mrem.

f. Other Federal Agencies

It has been estimated that approximately 2,000 Federal employees may not have been included in the reports of other agencies. To account for these employees, they have been assigned the mean dose for the Public Health Service.

Table IV-4

Summary of Atomic Energy Commission* Occupational Doses - 1969

Dose Range (rem/yr.)	Number of Persons	Percent of Total
0-1	98,625	95.8
(0-0.1)	(73,372)	(71.3)
(0.1-0.2)	(9,869)	(9.6)
(0.2-0.5)	(10,059)	(9.8)
(0.5-1.0)	(5,325)	(5.2)
1-2	2,554	2.5
2-3	1,313	1.3
3-4	335	0.3
4-5	86	0.1
5-6	4	
6-7	0	
7-8	0	
8-9	0	
9-10	0	
10-11	1	
11-12	0	
>12	0	
TOTAL	102,918	100

*Contractors and employees.

2. Nonfederal Activities

Nonfederal activities include Atomic Energy Commission licensees, agreement State licensees, X-ray use in the healing arts, and medical use of radium.

a. Atomic Energy Commission Licensees

Atomic Energy Commission regulations require that certain categories of licensees report annually all doses in excess of 1.25 rems. Administratively, many licensees find it easier to report all doses.[11] Data are also obtained as part of an annual survey of exposure levels determined by commercial film badge suppliers. The data provided by this survey represent approximately 29% of the total number of Atomic Energy Commission licensees. Of the 62,090 individual records, 95.8% indicated a dose of less than 1 rem.[12] The employees for whom records were provided are estimated to be approximately 40% of all occupationally exposed personnel operating under an Atomic Energy Commission license.[8]

All doses were reported in ranges as shown in Table IV-5. The total man-rem and mean dose values were calculated as previously described and are shown in Table IV-6. It is believed that they are overestimates of the actual individual dose to all employees because it is assumed that the 60% not reported were below 1.25 rem/yr. Thus, approximately 93,000 individuals are exposed to some level of radiation less than the mean annual exposure of those who may be expected to exceed 1.25 rem. Since the opportunity for exposure of the higher group would be up to 5 rem/yr., and the opportunity for exposure of the lower group is 1.25 rem/yr., a simple ratio of opportunity to be exposed has been used to calculate the mean of 54 mrem for the lower group. These doses are shown as nonreported Atomic Energy Commission licensees in summary tables below.

Table IV-5

Summary of Reporting Atomic Energy Commission (AEC) Licensee and Agreement State Licensee Occupational Doses - 1969

Dose Range (rem/yr.)	Number (and %) of Persons	
	AEC Licensee	State Licensee
0.0-0.1	45,785 (73.7)	17,041 (69.5)
0.1-0.2	5,224 (8.4)	2,084 (8.5)
0.2-0.5	5,777 (9.3)	2,550 (10.4)
0.5-1.0	2,710 (4.4)	1,422 (5.8)
1-2	1,489 (2.4)	785 (3.2)
2-3	583 (0.9)	319 (1.3)
3-4	191 (0.3)	98 (0.4)
4-5	109 (0.2)	73 (0.3)
5-6	64 (0.1)	49 (0.2)
>6	158 (0.2)	98 (0.4)
TOTAL	62,090 (100)	24,519 (100)

Table IV-6

Mean Annual Doses for Reporting Atomic Energy Commission Licensees - 1969

Activity	Employees	Man-rem	Mean Dose (mrem)
Medical	20,228	5,260	260
Major processor	1,789	495	276
Waste disposal	21	96	457
Radiography	1,894	752	397
Industrial	13,331	2,139	160
Academic	7,738	903	117
Reactors	2,302	497	216
Fuel processing	6,637	2,177	328
Packing and transport	335	22	66
Not specified	7,815	1,024	131
TOTAL	62,090	13,365	215

b. Agreement State Licensees

During 1969 there were 17 (22 at the end of 1970) States which had assumed regulatory authority over byproduct, source, and limited quantities of special nuclear materials. These agreement States continue to cooperate with the Atomic Energy Commission to insure compatible regulatory programs.[12]

Exposure data for 1970 comparable to that of Atomic Energy Commission licensees were provided for this study through the Atomic Energy Commission by 15 of the agreement States[8] (see Table IV-5). Since only 15 of the 17 agreement States were reported, an average of the reporting States was used to add 3,000 employees for the two States which did not report. The mean dose of the reporting States (Table IV-7) was used to determine man-rem as shown under nonreporting States in summary tables below.

c. X-ray Use in the Healing Arts

The most tenuous estimate developed in this study is the mean annual dose of nonfederal employees exposed during the use of radiation in diagnostic and therapeutic medical and dental radiology. The data for

Table IV-7

Mean Annual Occupational Doses for Agreement State Licensees - 1970

Activity	Employees	Man-rem	Mean Dose (mrem)
Medical	11,867	3,403	286
Processor	32	37	1,160
Waste disposal	256	766	2,991
Radiography	1,174	294	250
Industrial	6,479	1,490	230
Academic	3,980	499	125
Not specified	731	226	309
TOTAL	24,519	6,715	273

estimating this value has been obtained from a limited number of State health organizations which maintain central files on occupational doses and those which have conducted film badge surveys.

(1) Wisconsin

The State of Wisconsin has conducted film badge surveys on various categories of radiation workers for limited periods of time to evaluate the radiation protection procedures being followed by persons using x rays in the healing arts.

The most recent survey conducted involved 4,175 dentists for 1 month. The data obtained are shown in Table IV-8.[13] The mean annual dose was calculated to be 156 mrem.

Table IV-8

Wisconsin Dental Facility Survey - 1969 to 1970

Number Surveyed	Percentage in Dose Rate Range (mrem/week) 0 - 10	11 - 50	50 - 99	>100
4,175	93.6	5.8	0.6	0*
Assumed mean	1	30	75	140
Number	3,908	242	25	0
Total man-mrem/wk.	3,908	7,260	1,875	0

*Originally 4 individuals; review indicated improper handling of badge. Resurvey of these placed them in a lower range.

During 1969 a survey of 663 medical x-ray workers indicated an average total dose rate of 4,150 man-mrem/week.[14] Assuming that each individual works for 50 weeks/yr. the mean annual dose would be 313 mrem.

(2) Illinois

The State of Illinois requires that reports of all occupational exposure of employees who may receive a dose of greater than 0.312 rem/quarter be submitted to the Department of Public Health. The data for a portion of 1970 is shown in Table IV-9.[15] Although this program has been operating since 1964, it was not until 1970 that investigations of reported overexposures were required. It is believed that the reported data for 1970 represent a more valid mean dose than that of previous years when no attempt was made to determine if a badge exposure represented the exposure of the worker.

Table IV-9

Summary of Illinois Whole-body Radiation Doses - 1970

Category	Number of Reports	Mean Dose (rem/quarter)	Man-rem/ Quarter
Dentists	24	0.024	0.58
Physicians	75	0.043	3.22
Osteopaths	0	0	0
Chiropractor	10	0.003	0.03
Veterinarians	6	0.098	0.59
Podiatrists	0	0	0
Nursing institution	3	0.023	0.069
Hospitals	1,125	0.085	95.6
Clinics	45	0.080	3.6
Private laboratories	3	0.057	0.17

The data in Table IV-9 yield a dose of 324 mrem to these medical workers and 96 mrem to the dental workers.

(3) Maine

The State of Maine operated a statewide film badge service from 1956 to 1968. During the period 1956 to 1965, 580 individuals representing about 75% of all radiation workers in the State were monitored by this program. During fiscal year 1965, the average dose per month for all categories of workers was 20 mrem.[16]

(4) National Mean Dose

The data from the foregoing three States are the only readily available bases for establishing a national mean annual dose of 320 mrem per nonfederal medical x-ray worker and 125 mrem per nonfederal dental x-ray worker. These means are applied to the 194,541 medical x-ray workers and 171,226 dental x-ray workers in the United States.[17]

d. Medical Use of Radium

A survey of personnel occupationally exposed in radium therapy was conducted by the State of Wisconsin. The results of this study provided to the Public Health Service indicated that there may be as many as 185 medical radium workers per million population. Extending this to the population of the United States would indicate that there may be up to 37,925 individuals occupationally exposed in radium treatment who are not otherwise reported. The estimated number of radium treatments in Wisconsin is 800 per year. From 37 treatments monitored, the average total dose was 500 mrem per treatment or 400 man-rem per year from all treatments. This results in a mean annual dose of 540 mrem for the 740 medical workers in Wisconsin. This mean has been applied as a national mean dose from medical use of radium.

3. Summary

A summary of man-rem by reporting agency and occupation is shown in Table IV-10.

C. Internal Doses Incident to Occupation

It has been reported that reactor and accelerator workers as well as those involved with the manufacture and use of unsealed radioactive material can accumulate detectable amounts of radioactive material in the whole body and in various organs.[18]

In two studies, 91 radiopharmaceutical production workers and medical and paramedical personnel were subjected to whole-body counting over a period of 1 year.[19,20] Of the individuals monitored, approximately 88%

Table IV-10

Total Annual Whole-body Man-rem by Reporting Group and Occupation - 1969 to 1970

Activity	Air Force	Army	Navy	State Licensee	AEC Licensee	AEC	PHS	Non-federal	Nonreporting Licensee State	Nonreporting Licensee AEC
Healing arts	736	366	477	3,403	5,260		65	104,136		
Medical x ray	(405)									
Dental x ray	(264)							(62,253)		
Radionuclides	(53)							(21,403)		
Veterinary x-ray	(14)									
Medical radium								(20,480)		
Industrial practice	394	269	10,402	1,784	2,891					
Radionuclides	(229)			(1,490)	(2,139)					
Radiography	(165)			(294)	(752)					
Reactors	100	73			497					
Waste disposal				766	96					
Fuel processing					2,177					
Packaging & transport					22					
Radar	96									
Special weapons	65									
Academic				499	903					
Not specified	164			226	1,024	20,361			819	5,022
Major processing				37	495					

had detectable body burdens although the average body burden was a very small percentage of the maximum permissible body burden (1.3% for radiopharmaceutical workers). None of the individuals in these studies had more than 15% of a maximum permissible body burden. During the study of radiopharmaceutical workers up to 19 nuclides were identified while nine nuclides were found in the medical and paramedical personnel.

Because of the sparsity of data and difficulty in determining the contribution of internal emitters to population dose it is not included in estimates of population dose.

D. Population Dose from Occupational Exposure

Using reported numbers of workers and judicious estimates in non-reported areas, a value for the number of workers in the population was derived. As shown in Table IV-11, this number is 771,814 or 3.76 per thousand population.

As shown in Table IV-11, the total man-rem from occupational exposure is 163,922; mean annual dose is 210 mrem/worker. The percentage of employees in dose ranges by agency are shown in Table IV-12. For the population of the United States, assuming the dose indicated by dosimetry to be a whole-body dose, the calculated whole-body dose is 0.8 mrem per capita.

E. Population Dose from Occupational Exposure,1960 to 1970

The evaluation of occupational dose during the period 1960 to 1970 is complicated by a lack of appropriate monitoring data. In many cases, the personnel monitoring systems of various agencies were relatively new or nonexistent in 1960. In addition, the reliability of dosimetry data was more questionable than it currently is and the appropriate persons to be monitored were doubtful.

For many agencies the early 1960's marked the beginning of active radiation protection programs and serious efforts to reduce dose to the lowest practicable level were introduced.

From the data available,it may be reasonably concluded that the average dose per worker was reduced during this period. In general, the percentage of workers in the range from 0 to 1 rem increased and the total number of doses in excess of 5 rem/yr. decreased. In 1960,it was

Table IV-11

Total Annual Occupational Whole-body Doses - 1969 to 1970

Agency	Number of Workers	Man-rem	Mean Dose per Worker (mrem)	Average Dose to U.S. Population (mrem)
Army	7,445	744	100	0.003
Air Force	17,591	1,555	88	0.007
Navy	55,051	10,879	198	0.05
AEC	102,918	20,361	198	0.10
PHS	508	65	129	0.0003
Other Federal	2,000	258	129	0.001
AEC licensees	62,090	13,365	215	0.07
Agreement State	24,519	6,715	274	0.03
Nonfederal medical x ray	194,451	62,253	320	0.30
Nonfederal dental x ray	171,226	21,403	125	0.10
Medical radium	37,925	20,480	540	0.10
Nonreporting AEC licensees	93,000	5,022	54	0.02
Nonreporting agreement State	3,000	822	274	0.004
TOTAL	771,814	163,922	210	0.8

reported that at two major Atomic Energy Commission facilities, Oak Ridge National Laboratory and Hanford facilities, the annual average exposure of radiation workers was 0.4 R and 0.2 R, respectively.[21] For these reasons an annual average dose of 300 mrem/worker has been used for 1960.

The numbers of workers in the population in 1960 are also obscured by lack of reliable records. To determine the number of medical workers (excluding dental) an annual rate of increase in demand for service of 7.1% has been used.[22] Extrapolating from 1970 data, shown in Table IV-13, the number of medical radiation workers per thousand population would be 0.88 or 161,000 workers.

For dental workers, although the ratio of dentists to the population has decreased below the 1950 ratio, the ratio of allied workers has in-

Table IV-12

Percent of Employees in Annual Dose Ranges - 1969 to 1970

Reporting Agency	Number of Employees	Dose Ranges (rem)					
		0 - 1	1 - 2	2 - 3	3 - 4	4 - 5	>5
AEC	102,918	95.8	2.5	1.3	0.3	0.1	0.0
State licensees[a]	24,519	96.2	3.2	1.3	0.4	0.2	0.6
AEC licensees[b]	62,090	95.8	2.3	0.9	0.3	0.1	0.3
Army	22,790 (7,445)[c]	99.0	-	-	1.0	-	-
Air Force	34,975 (17,591)[c]	99.0	-	-	1.0	-	-
PHS	508	99.0	-	-	1.0	-	-
Navy	55,051	Not available					

[a] 15 of 17.

[b] ~40%.

[c] No. >10 mrem/yr.

Table IV-13

Job Category Data - 1969 to 1970

Category	Number of Workers (thousands)	Workers/ Thousand	Annual Man-rem (thousands)	Average Dose to U.S. Population (mrem/yr.)
Medical x ray	203.6	0.99	63	0.3
Dental x ray	178.6	0.87	22	0.1
Medical radionuclides	33.5	0.16	8.8	0.04
Medical radium	38.0	0.18	20	0.1
Research and industrial use	318.3	1.55	49	0.2

creased[23] and the ratio of radiation workers is believed to be relatively constant from 1960 to 1970. For this reason the value of 0.87 workers per thousand or 159,000 workers has been used for dental practice.

There was undoubtedly a significant change in the numbers of radiation workers involved in industrial applications from 1960 to 1970. The advent of a nuclear-powered naval force during this period increased the number of workers by several thousand. It was also reported in 1960 that the Atomic Energy Commission classified 66,000 employees as radiation workers.[21] It has been assumed that the workers per thousand in this area did not exceed 0.75, or 137,000 workers.

The total radiation workers as derived above is 457,000 and represents 0.25% of the 1960 population as opposed to 0.2% reported by the Federal Radiation Council in that year.[21] Using this number of workers and a mean annual dose of 300 mrem/worker, the resulting population dose is 0.8 mrem per capita (Table IV-14).

Table IV-14

Estimated Annual Whole-body Doses to the United States Population from Occupational Expos.re
(mrem)

	Year				
Practice	1960	1970	1980	1990	2000
Medical	0.3	0.4	0.4	0.4	0.3
Dental	0.3	0.1	0.1	0.1	0.1
Industrial	0.2	0.3	0.3	0.4	0.5
TOTAL	0.8	0.8	0.8	0.9	0.9

F. Population Dose from Occupational Exposure, 1980 to 2000

To estimate the population dose through the year 2000, the following assumptions have been used.

1. The number of workers in dental practice will remain constant at 0.87 per thousand.

2. The demand for medical care will increase at a lesser rate until it becomes constant at 1.5 per thousand in 1990. The value for 1980 has been assumed to be 1.3 per thousand.

3. The greatest increase will be from industrial usage, particularly from the increase in nuclear power facilities and the required ancillary support activities. The number of workers in this category will increase continually through the period under consideration. The number of workers per thousand estimated for 1980, 1990, and 2000 are 1.7, 2.0, and 2.2, respectively.

4. Through legislation and education, the practice of good radiation protection methods will become more widespread among the users of ionizing radiation. Without consideration of development of new techniques, the enforcement of currently recognized good practice will substantially reduce the mean annual dose per worker. By the year 2000, the mean for medical workers should approach the current mean for Federal employees. It is assumed that this will be for 1980, 1990, and 2000: 300 mrem, 250 mrem, and 200 mrem, respectively. A similar reduction in occupational exposure from dental practice is assumed to result in mean annual doses of 110 mrem, 100 mrem, and 95 mrem, respectively.

5. In industrial and research activities the mean annual dose will probably increase. Although the more widespread use of good protection methods will lessen the impact, it is anticipated that the mean annual doses from these sources will approach 225 mrem by the year 2000. For 1980 and 1990, 175 mrem and 200 mrem have been used as the mean.

The foregoing assumptions have been used to estimate the future population doses shown in Table IV-14.

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V. MISCELLANEOUS RADIATION

There are several sources of exposure to ionizing radiation to which the general public may be exposed that are not discussed in the previous sections of this report.

A. Television Receivers

In 1968 a survey of 1,124 color television receivers was performed in the metropolitan Washington, D.C., area.[1] The average rate of emission of ionizing radiation 5 cm from the front face of these receivers was found to be 0.043 mR/hr. This survey also analyzed the viewing habits of the family members in the households where receivers were surveyed.

Based on the 1968 survey, estimates of potential doses to various organs were derived. For purposes of this report, the female gonadal dose has been selected to represent the somatic dose for determination of total man-rem from this source.

To determine the total man-rem and mean per capita dose as shown in Table V-1, the following assumptions have been made.

1. The viewing habits of the population are essentially the same as those in the 1968 survey and will not change.
2. The population exposed in 1970 is approximately 50% of the total population. This is based on 24% of the households having color television in 1968[3] and 39% in 1969, and a production rate[2] of 500,000 color television receivers per month.
3. The population exposed in 1980 will approach 100%.
4. The trend in reduction of emission rate from television receivers noted in 1968 and 1969 will continue with improved design and new developments.[3] A reduction of average emission rate to 0.025 mR/hr. at 5 cm by 1980 is assumed. Since the estimates of dose mentioned above[1] are based on a linear function of exposure rate a proportional reduction in dose is expected.[2]

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The estimates are shown in Table V-1. These may be high by as much as a factor of two because of instrument calibration in the 1968 survey.[2,3]

Table V-1

Total Annual Average Whole-body Doses from Television Receivers - 1970 to 2000

Year	1970	1980	1990	2000
Emission rate (mR/hr. at 5 cm)	0.043	0.025	0.025	0.025
Mean dose (mrem)				
Age <15 yr.	0.4	0.2	0.2	0.2
Age >15 yr.	0.2	0.1	0.1	0.1
Population at risk (millions)				
Age <15 yr.	28	63	80	89
Age >15 yr.	75	174	197	232
Man-rem	26,200	30,000	35,700	41,000
Total population (millions)	205	237	277	321
Mean per capita dose (mrem)	0.1	0.1	0.1	0.1

B. Consumer Products Containing Radioactive Material

For many years, radium has been used in items readily available to the general public. Some of these uses are: fire detection devices, static eliminators, gauges, electronic tubes, and laboratory balances. In many instances the user is unaware that radium is incorporated into the product or that a potential radiation hazard exists.[4,5] In recent years, tritium and ^{147}Pm have also been used as radiation sources in self-luminous devices. Luminous watches appear to be the greatest source of population exposure from the devices mentioned above.

The number of watches containing radioactive materials is difficult to estimate. In the case of watches containing radium, no United States data are available. However, assuming usage similar to that in foreign countries[4] as much as 35 to 50% of the adult United States population may have possessed a watch containing radium in the late 1960's. Tritium compounds imported into the United States together with domestic manufacture indicate that 25 million watches containing 1 to 5 mCi of tritium were sold during the year June 1969 to June 1970.[6] During this same period approximately 1 million watches with 30 to 50 μCi of ^{147}Pm were made available to the public.[6]

Doses from radium watches reported in 1963 appear to indicate whole-body doses between 1.3 and 5.3 mrem/yr.[7] Whole-body doses from 1 to 4 mrem/yr. have been estimated, using a quality factor of 1.7, in persons using wrist watches containing tritium,[7,8] while watches containing ^{147}Pm give doses in the μrem range.[8]

Other luminescent items containing radioactivity, particularly self-luminous military devices, make slight contributions to the total population dose, the maximum estimated to be 0.01 mrem/person/yr. to the United States population.

The estimated annual whole-body dose to the population of the United States in 1960 is 1 mrem, and for 1970, 1.5 mrem. The projected average for 1980 is 1 mrem and 0.01 mrem for 1990 and 2000. These estimates reflect increased use of radium and tritium in watches from 1960 to 1970 and increased use of ^{147}Pm from 1970 to 2000.

C. Air Transport

Passengers and crew of aircraft are subjected to increased rates of exposure during high altitude flight from galactic cosmic radiation. Preliminary data[9] show that the average increase in dose equivalent rate at an altitude of 30,000 ft. (approximate conventional jet aircraft altitude) may be 0.7 mrem/hr. and at 60,000 ft. (supersonic transport aircraft altitude) 1.1 mrem/hr.

There were 125 billion passenger-miles flown by United States airlines during 1970.[10] It is estimated that the average air speed during this period was 400 mi./hr. (average in 1968 was 389 mi./hr.).[11] Using these values, 310 million passenger-hours were flown by United States airlines during 1970. It is assumed that all flights were at conventional jet altitude.

As a result of air transport, approximately 200,000 man-rem were accumulated by passengers.

Air crew members are considered here as a special occupational group. The number of air crew members has not been obtained. However, the total number[11] of aircraft owned and leased by air carriers in 1969 was 2,638.

Assuming an average crew of five, there could be up to 13,000 air crew members employed. To include military air crews, it is estimated that there are approximately 15,000 individuals serving as air crew members operating at conventional jet altitudes.

Using a value of 80 hr. flight time per month,[10] the average crew member receives a dose of 670 mrem/yr.

From high altitude flight, the population dose is estimated to be 210,000 man-rem during 1970 or a mean United States per capita dose of 1.0 mrem.

For projected doses from air transport, super-sonic altitudes must be considered. It is indicated that the dose to passengers will be reduced because of the shorter time at altitude even though the dose rate is increased.[9] No assumptions on projected air crew dose have been made. Because the conditions of air transport are in doubt, the projected doses are proportional to population increase only.

The foregoing estimates are based on limited studies which should be re-evaluated as more data become available.

D. Summary

The total estimated annual whole-body doses from miscellaneous sources to the United States population are summarized in Table V-2.

Table V-2

Total Annual Average Whole-body Doses to the United States Population from Miscellaneous Sources

	Doses							
	Television		Consumer Products		Air Transport		Total	
Year	mrem	man-rem	mrem	man-rem	mrem	man-rem	mrem	man-rem
1960	0	0	1.0	180,000	1.0	180,000	2.0	360,000
1970	0.1	26,000	1.5	310,000	1.0	210,000	2.6	550,000
1980	0.1	30,000	1.0	240,000	1.0	240,000	2.1	510,000
1990	0.1	36,000	0.01	3,000	1.0	280,000	1.1	320,000
2000	0.1	41,000	0.01	3,000	1.0	320,000	1.1	360,000

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VI. SUMMARY

The study reported in this document is that part of the overall review of the bases for radiation guidance that is concerned with estimates and predictions of ionizing radiation doses in the United States from all sources. Estimates or predictions were made for each decade of the period 1960 to 2000. The results are presented in Table VI-1 and Figures VI-1 and VI-2 and are summarized below.* It should be noted that in this summary more digits are shown than are actually significant in order to indicate trends. A number of sources were found to contribute insignificantly to the total annual dose to the United States population. The sum of the doses contributed by these sources is also insignificant.

A. Environmental Radiation

A major source of radiation doses in the United States is natural radiation. The total estimated annual whole-body dose increases from 23.8 million man-rem in 1960 to 41.7 million man-rem in the year 2000 from cosmic and natural terrestrial sources. The increase is due exclusively to increases in population size. Global fallout from nuclear explosives tests contributed about 1 million man-rem (whole-body) in 1960, a high of 2.4 million man-rem in 1963, and 0.8 million man-rem in 1970. Future doses from fallout for 1980 are predicted to be 1.1 million man-rem, increasing to 1.6 million man-rem in 2000, the increase again being due to population growth. The total dose contributed by all other environmental sources increases from 0.015 million man-rem in 1960 to 0.15 million man-rem in 2000.

B. Medical Radiation

By far the greatest portion of the man-made radiation dose to the United States population is due to exposure accrued during medical diagnostic

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*Comparisons based on whole-body doses except for doses from medical radiation, in which case the abdominal dose, an index of somatic dose, is used.

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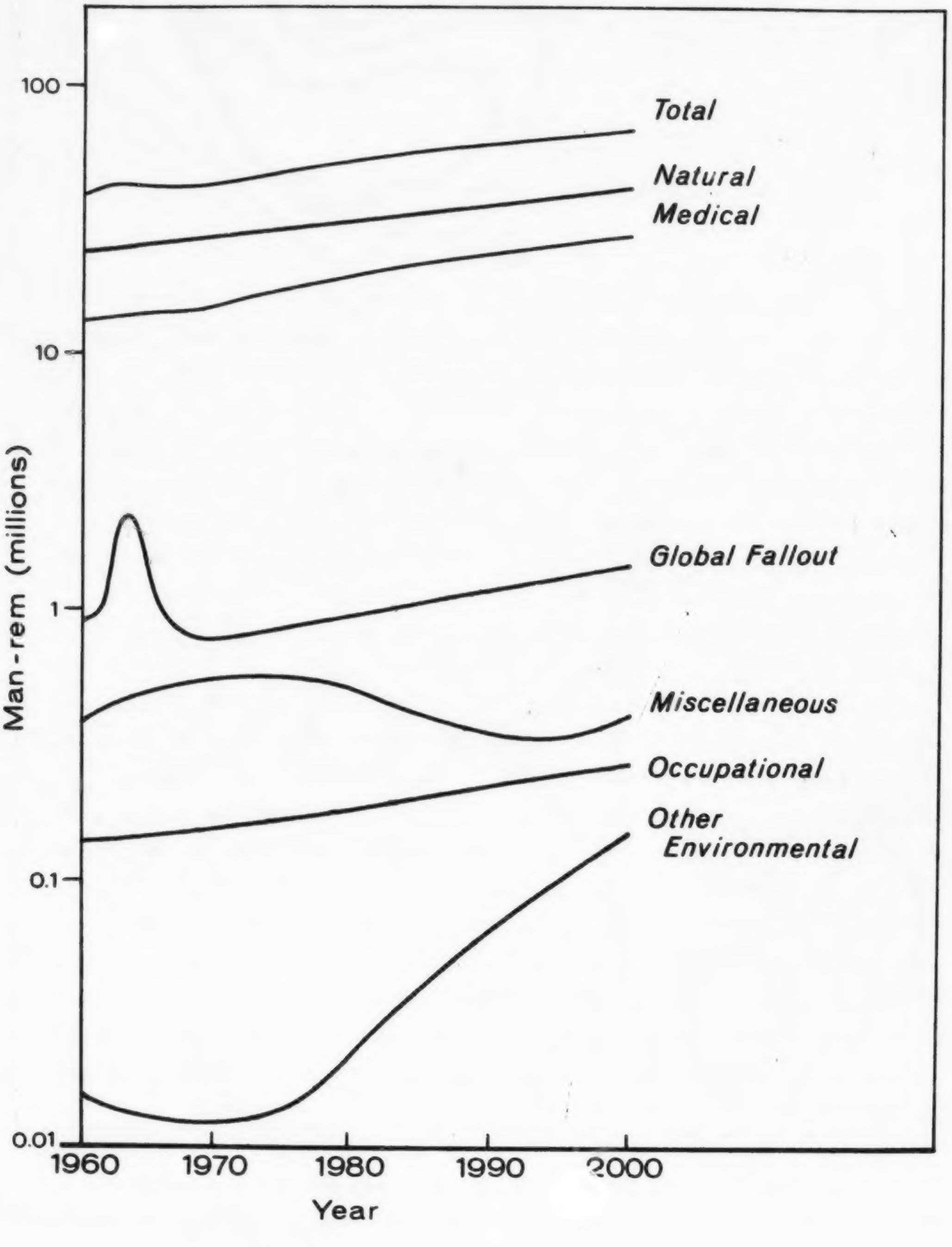

Figure VI-1. Summary of Estimated Whole-body Radiation Man-rem Doses in the United States

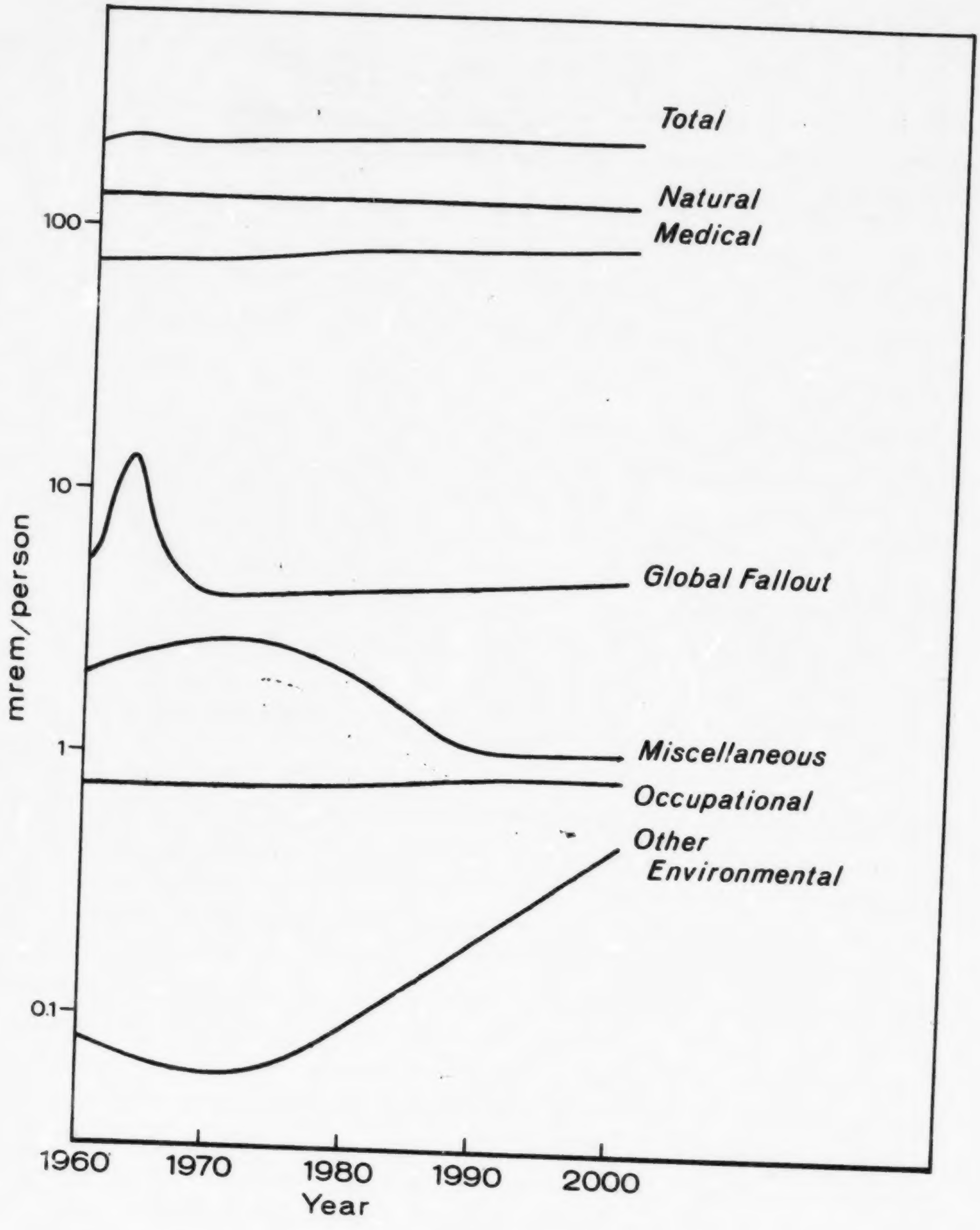

Figure VI-2. Summary of Estimated Average Whole-body Radiation Doses in the United States (mrem/person)

Table VI-1

Summary of Whole-body Annual Radiation Doses in the United States - 1960 to 2000

	Man-rem (millions) for Years				
Radiation Source	1960	1970	1980	1990	2000
Environmental					
Natural	23.8	26.6	30.8	36.0	41.7
Global fallout	1	0.82	1.1	1.3	1.6
All other	0.015	0.012	0.022	0.062	0.15
Subtotal	24.8	27.4	31.9	37.4	43.4
Medical					
Diagnostic*	13.2	14.8	17.1	19.9	23.1
Radiopharmaceuticals	0.07	0.4	3.3	4	5
Subtotal	13.3	15.2	20.4	23.9	28.1
Occupational	0.14	0.16	0.19	0.24	0.28
Miscellaneous	0.36	0.55	0.51	0.32	0.36
TOTAL	38.6	43.3	53.0	61.9	72.1
Population (millions)	183	205	237	277	321
Per capita dose (mrem)	211	211	224	224	225

*Medical diagnostic man-rem doses based on an index of somatic dose, the "abdominal dose." For radiation therapy an annual per capita genetically significant dose of approximately 5 mrem was estimated for the year 1966, but an index of somatic dose is not considered applicable.

procedures. Medical diagnostic radiology accounts for at least 90 percent of the total manmade radiation dose to which the United States population is exposed. This is at least 35% of the total radiation dose from all sources (including natural radioactivity). This comparison is based on an interim index of somatic dose, the "abdominal dose," which was derived from ovarian doses reported by the Public Health Service in 1964 and 1970. The majority of this dose is accrued through medical diagnostic radiography and fluoroscopy, with lesser doses accrued through the diagnostic uses of radiopharmaceuticals and dental radiography. Estimates indicate that the annual per capita "abdominal dose" from these sources to the whole population, as estimated some time during the past decade, were 72 mrem, 1 mrem and less than 0.3 mrem respectively, from medical diagnostic radiography and fluoroscopy in 1970, the diagnostic uses of radiopharmaceuticals in 1966, and dental radiography in 1964. It appears that the mean abdominal dose for the U.S. population as determined in 1964 and 1970 has remained relatively stable during the two study years. However, since the magnitude of the uncertainty surrounding the figures upon which the abdominal dose is based has not yet been determined, the magnitude of whatever change may have occurred between 1964 and 1970 cannot be determined at this time. The per capita dose to the exposed population (i.e., persons receiving examinations) were, of course, significantly higher than those to the whole population. The estimated total man-rem dose to the whole U.S. population in 1970 from the uses of radiation in the healing arts is estimated to be 15.2 million man-rem exclusive of occupational exposure and radiation therapy.

The "genetically significant dose" is an index of radiation received by the genetic pool. Estimates of genetically significant doses indicate values of 36 mrem (based on preliminary data from the 1970 U.S. Public Health Service Survey) from medical and dental diagnostic radiation, 5 mrem from radiation therapy in 1966, and 0.3 mrem from the diagnostic uses of radiopharmaceuticals (also in 1966). Preliminary U.S. Public Health Service information indicates a drop in genetically significant dose in 1970 relative to the 1964 value of 55 mrem. However, as above, since the degree of uncertainty of these values have not as yet been determined, the magnitude of the change which may have occurred between 1964 and 1970 is not clear at this time.

Projections of doses from diagnostic medical radiography must take into consideration a variety of complex variables. Review of several reports on the rate of increase of radiographic examinations leads to the conclusion that, in the past decade, the rate of radiographic examinations increased between 1 and 4 percent per year. Some of this increase appears to be due to the expansion of radiological services to persons who previously did not have such care available. Furthermore, there is some evidence that technical improvements may be keeping pace with increasing usage. If this balance between increasing usage and technical improvement is real, and if it continues, the man-rem dose from diagnostic medical radiation would increase through population increase alone to about 23.1 million man-rem by the year 2000. Even before the year 2000, if the current rate of increase in the uses of radiopharmaceuticals should continue to 1980, the whole-body man-rem dose from this source to the U.S. population could be greater than 3.3 million man-rem, or approximately 15% of that from other medical sources.

The delivery of radiation for therapy is exluded in estimates of accumulated man-rem doses to the population. There is no significant information to indicate the direction that the doses from radiation therapy will take in the future even though its use might increase.

Extrapolations and projections made in this study must be considered in light of the uncertainties surrounding the base measurements, the assumptions employed and the changing state of medical technology. If technical improvements can keep pace with increased usage rates, it can be concluded, based on the information presently available and discussed in this report, that the annual per capita population dose from diagnostic medical radiography could remain stable.

Finally, it should be noted that direct comparisons of medical x-ray doses to the population with those from other sources is difficult because x rays are administered purposefully to individuals at the discretion of practitioners, and because they are delivered at higher dose rates to limited areas of the body.

C. Occupational Radiation

The contribution of occupational exposures to total United States per capita dose is estimated to be less than 1 mrem/yr. The major portion of this dose during 1960 and 1970 was incurred through the use of ionizing radiation in the practice of medicine and dentistry.

Increased industrial use of ionizing radiation, particularly the projected increase in nuclear power production, will increase the per capita dose by approximately 0.1 mrem/yr. by 1990. During the 1990's the population dose from industrial sources and the practice of medicine and dentistry will probably be about the same. The total dose from occupational exposure to the United States population is estimated to have been 0.14 million man-rem in 1960 and is projected to reach 0.28 million man-rem in the year 2000.

D. Miscellaneous Radiation

Miscellaneous radiation sources (e.g., television, consumer products, and air transport) contribute to the radiation dose of the population of the United States. Estimated annual average whole-body doses to the population are 2.0 and 2.6 mrem (0.36 million and 0.55 million man-rem) for 1960 and 1970, respectively. Projected annual doses are 2.1 mrem (0.51 million man-rem) for 1980 and 1.1 mrem (0.32 million and 0.36 million man-rem) for 1990 and 2000.

E. Total Man-rem

The total man-rem to the United States population will increase in the future due mainly to population growth. It will approximately double between 1970 and 2000, 43 million to 72 million man-rem, the population increasing from 205 million to 321 million.

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